Technical Support Document

State of Colorado

ANALYSES IN SUPPORT OF EXCEPTIONAL EVENT FLAGGING AND EXCLUSION FOR THE WEIGHT OF EVIDENCE ANALYSIS

Supporting the

Denver Metro/North Front Range
State Implementation Plan
for the 2008 8-Hour Ozone
National Ambient Air Quality Standard

Approved: November 17, 2016

CDPHE CO COLORADO Department of Public Health & Environment

REGIONAL AIR QUALITY COUNCIL

ANALYSES IN SUPPORT OF EXCEPTIONAL EVENT FLAGGING AND EXCLUSION FOR THE WEIGHT OF EVIDENCE ANALYSIS

1.0 Introduction

This report will provide abbreviated documentation to support the exceptional event flagging and exclusion of ozone exceedances caused by stratospheric intrusions and wildfire smoke. A summary of the high-concentration events excluded from base year design value calculation as a part of Weight of Evidence analysis for the Ozone SIP is presented in Table 1, and this is a repeat of Table 35 in the main ozone SIP document.

Table 1 – Ozone Monitoring Data Flagged as Exceptional Events and Excluded from Base Year Design Value Calculation.

Date	Chatfield	Rocky Flats North	NREL	Fort Collins West	Exception Event Type		
					Stratospheric Ozone Intrusion	Wildfire Smoke Influence	
	8–hour Ozone Concentrations (ppb)					Regional	Local
April 13, 2010	79	—	—	—	x		
April 14, 2010	—	—	—	75	x		
June 7, 2011	84	—	—	—	x		
May 15, 2012	—	—	—	76			x
June 17, 2012	—	—	—	77			x
June 22, 2012	—	101	83	93			x
July 4, 2012	96	92	95	76		x	
July 5, 2012	—	88	81	—		x	
August 9, 2012	98	84	88	86		x	
August 21, 2012	80	80	80	—		x	
August 25, 2012	—	80	—	—		x	
August 31, 2012	—	—	—	80		x	
August 17, 2013	—	86	84	87		x	

2.0 Stratospheric Intrusions of Ozone in 2010 and 2011

The first 3 events in Table 1 were exceptional events associated with stratospheric intrusions of ozone (natural ozone that is at very high concentrations in the stratosphere). These intrusion events are associated with folding of the tropopause. The tropopause is the location in the atmosphere where the troposphere meets the stratosphere. Folding of the tropopause can bring a tongue or lobe of stratospheric air downward into the troposphere in the wake of strong upper level storm systems or troughs. According to Holton et al. (1995), a tropopause fold is "a process in which a thin band of stratospheric air intrudes more or less deeply into the troposphere…" This phenomenon and its relationship to ozone has been the subject of many research papers including classic papers by Danielsen (1968) and Shapiro (1980). In the mid-latitudes of the northern hemisphere, it is most likely to occur in the spring (March through June). The folding and descent of the tropopause typically occurs south and southwest of the surface and upper-level low pressure systems and behind the advancing cold front associated with a strong spring storm (Browning et al., 2000). This folding and descent of stratospheric air into the troposphere brings with it dry stratospheric air, stratospheric ozone, and other chemical constituents and atmospheric properties associated with the stratosphere (Browning et al., 2000; Danielsen, 1968; and Shapiro, 1980). These chemical constituents and properties are often diagnostic of the intrusion itself in the context of the path and progression of a storm system across an area.

One of the most important diagnostic properties of a stratospheric intrusion is isentropic potential vorticity or IPV. This property is a function of a parcel of air's rotation and its static stability. In the absence of heating or friction, IPV is conservative. In other words, a parcel of air will have the same IPV as it flows from one location to another. IPV therefore serves as a tracer for stratospheric air. IPV is high in the stratosphere and low in the troposphere. As a fold in the tropopause introduces stratospheric air into the troposphere, the intruding air will often maintain high values of IPV.

IPV has arcane units, but it is usually represented in terms of potential vorticity units or PVU. Air in the troposphere typically has IPV values less than 1 PVU. For atmospheric scientists studying the tropopause (the boundary between the stratosphere and the troposphere) the most common choice of values of IPV considered to be representative of the tropopause is 2 PVU (Kunz et al., 2011). Kunz et al. (2011) have found that IPV at the tropopause can vary between 1.5 and 5.0 PVU.

Stratospheric air is also very dry. Increases in winds and decreases in relative humidity can also be diagnostic of an intrusion. Total column ozone increases in the center of the kind of upper-level low pressure that usually is associated with intrusion events.

The work of Langford et al. (2009) demonstrates that stratospheric intrusions can cause elevated ozone along Colorado's Front Range and exceedances of the National Ambient Air Quality Standards (NAAQS):

> "A deep tropopause fold brought 215 ppbv of O3 to within 1 km of the highest peaks in the Rocky Mountains on 6 May 1999. One-minute average O3 mixing ratios exceeding 100 ppbv were subsequently measured at a surface site in Boulder, and daily maximum 8-hour O3 concentrations greater or equal to the 2008 NAAQS O3 standard of 0.075 ppmv were recorded at 3 of 9 Front Range monitoring stations. Other springtime peaks in surface O3 are also shown to coincide with passage of upper level troughs and dry stable layers aloft. These results show that the stratospheric contribution to surface ozone is significant, and can lead to exceedance of the 2008 NAAQS O3 standards in a major U.S. metropolitan area."

Langford and coauthors describe events that occurred in April and May of 2009 that are likely very similar to the events in question in this report. Both the State of Wyoming Department of Environmental Quality/Air Quality Division and CDPHE have previously documented exceedances of the 8-hour NAAQS caused by similar intrusion events:

https://www.epa.gov/sites/production/files/2015-05/documents/june_14_2012_bigpiney_boulder_si_package.pdf

http://deq.wyoming.gov/media/attachments/Air%20Quality/Monitoring/Exceptional%20Events/2012-0606_Stratospheric-Intrusion-Ozone-Event_Thunder%20Basin_WY.pdf

http://www.colorado.gov/airquality/documents/TSD_O3_Intrusion_Event_052410.pdf

Langford and coauthors indicate that their "findings support the conclusion of Lefohn et al. (2001) that " intrusions "can lead to high surface O3 events in the western U.S. during springtime that exceed current NAAQS standards." Other scientists (Karyampudi et al., 1996) have shown that localized or mesoscale tropopause folding occurs along the Front Range. The passage of a storm system across the mountain barrier leads to a leeward, wave-pattern enhancement of the intrusion east of the Divide. Data presented in this report will show that the pattern of high ozone concentrations in Colorado during an intrusion event can be consistent with enhanced folding and the downward mixing and transport of stratospheric ozone on the eastern side of the Continental Divide. The Air Pollution Control Division believes that enhanced intrusions just east of the Front Range have been observed on a number of occasions during the spring in the last several years.

The April 13 and 14, 2010 intrusion event in Colorado was caused by a strong spring storm with a 500 millibar (mb) upper level low of 5460 meters over Montana on April 13 (see Figure 1). Figure 1 shows the 500 mb wind streamlines and the center of the low pressure system from the 18Z analysis run of the NAM12 model for April 13, 2010. The NAM12 model data used to describe this event is available at the NOAA National Operational Model Archive and Distribution System (NOMADS) data site (http://nomads.ncdc.noaa.gov/). Figures 2 and 3 show the GOES derived total column ozone in Dobson Units (DU) for 1900 GMT on April 13 and 1800 GMT on April 14, respectively. Figure 2 shows very high total column amounts of 350 to 450 DU over Colorado associated with the upper low in Figure 1. The surface low was located over the northern Great Plains, and this low and surface relative humidity are depicted in Figure 3. This event caused high-concentrations at Chatfield on April 13 (79 ppb for a maximum 8-hour value) and Fort Collins West (75 ppb for a maximum 8-hour value) on April 14, and these values were excluded from base year design value calculations in a SIP Weight of Evidence analysis.

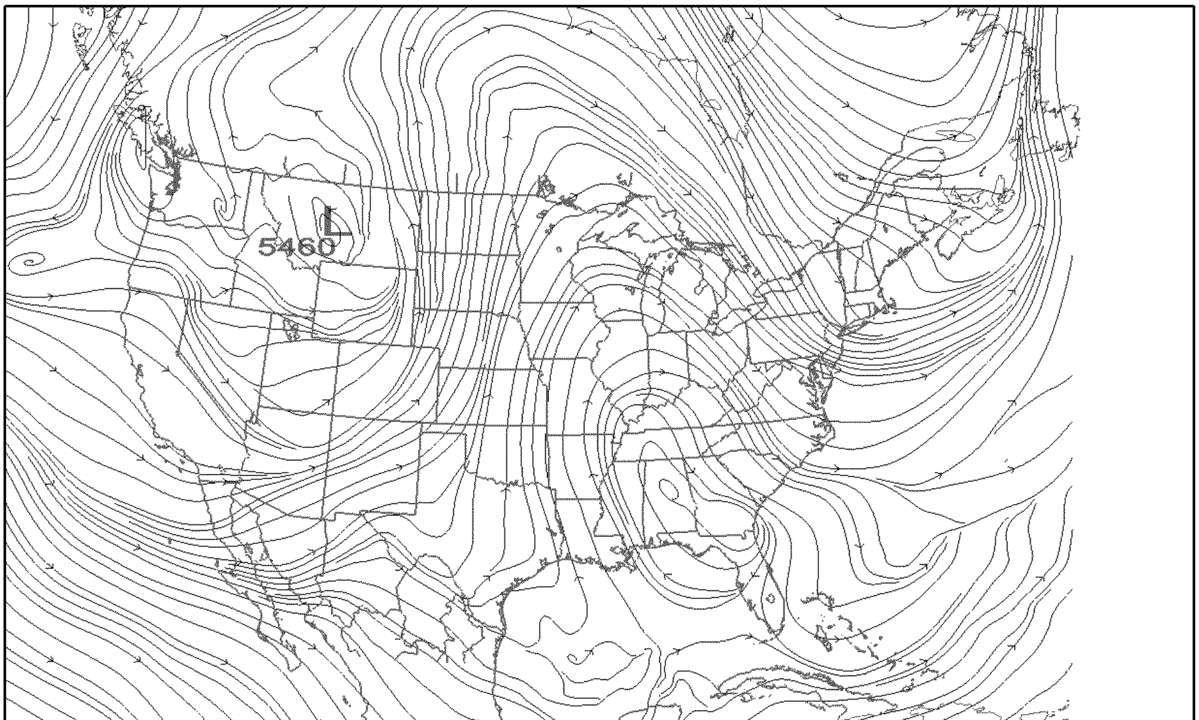

Figure 1. 500 mb wind streamlines and center of low pressure from the 18Z analysis run of the NAM12 model for April 13, 2010.

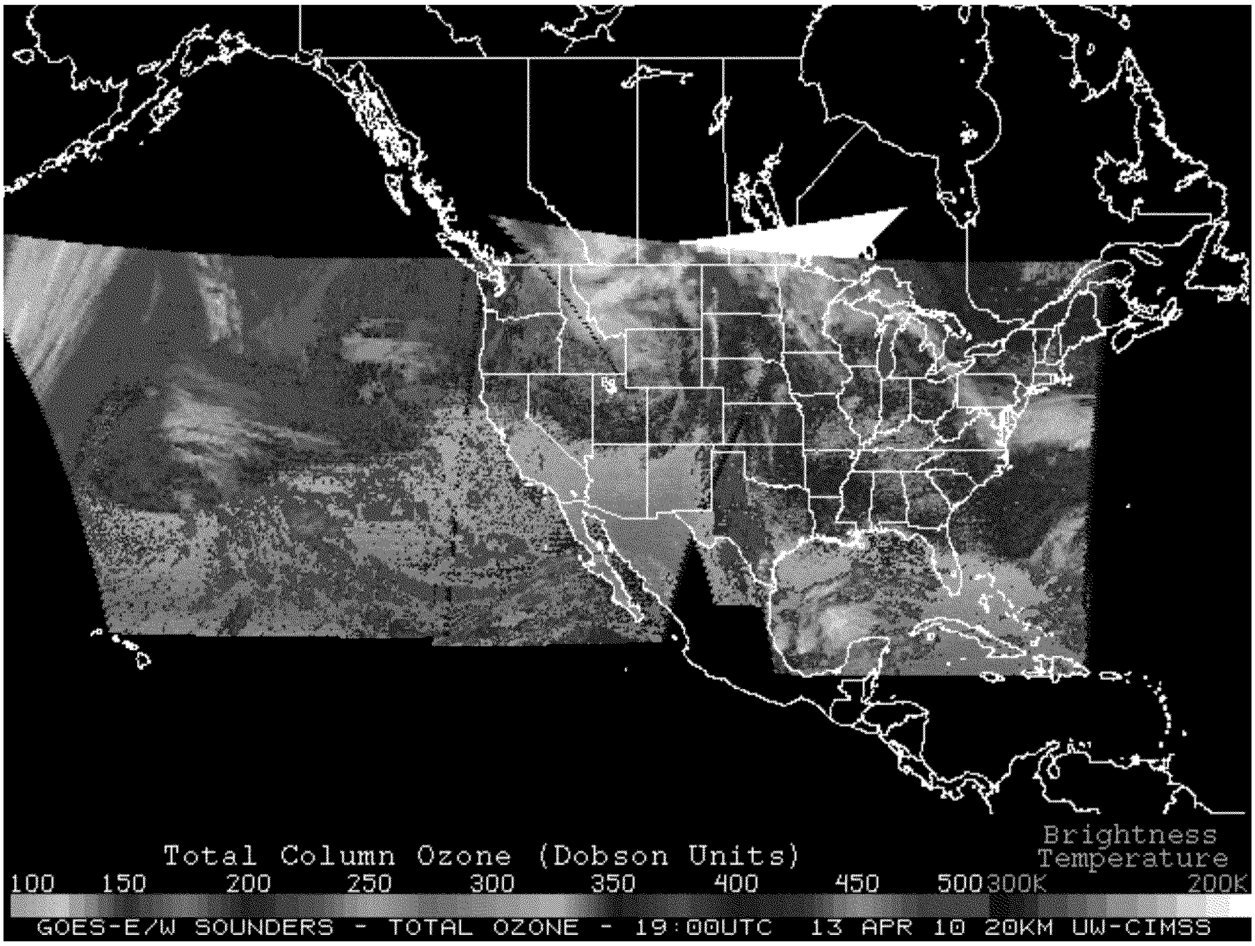

Figure 2. Total column ozone in DU at 1900 GMT April 13, 2010, derived from GOES satellite data (https://cimss.ssec.wisc.edu/goes/rt/viewdata.php?product=o3_us).

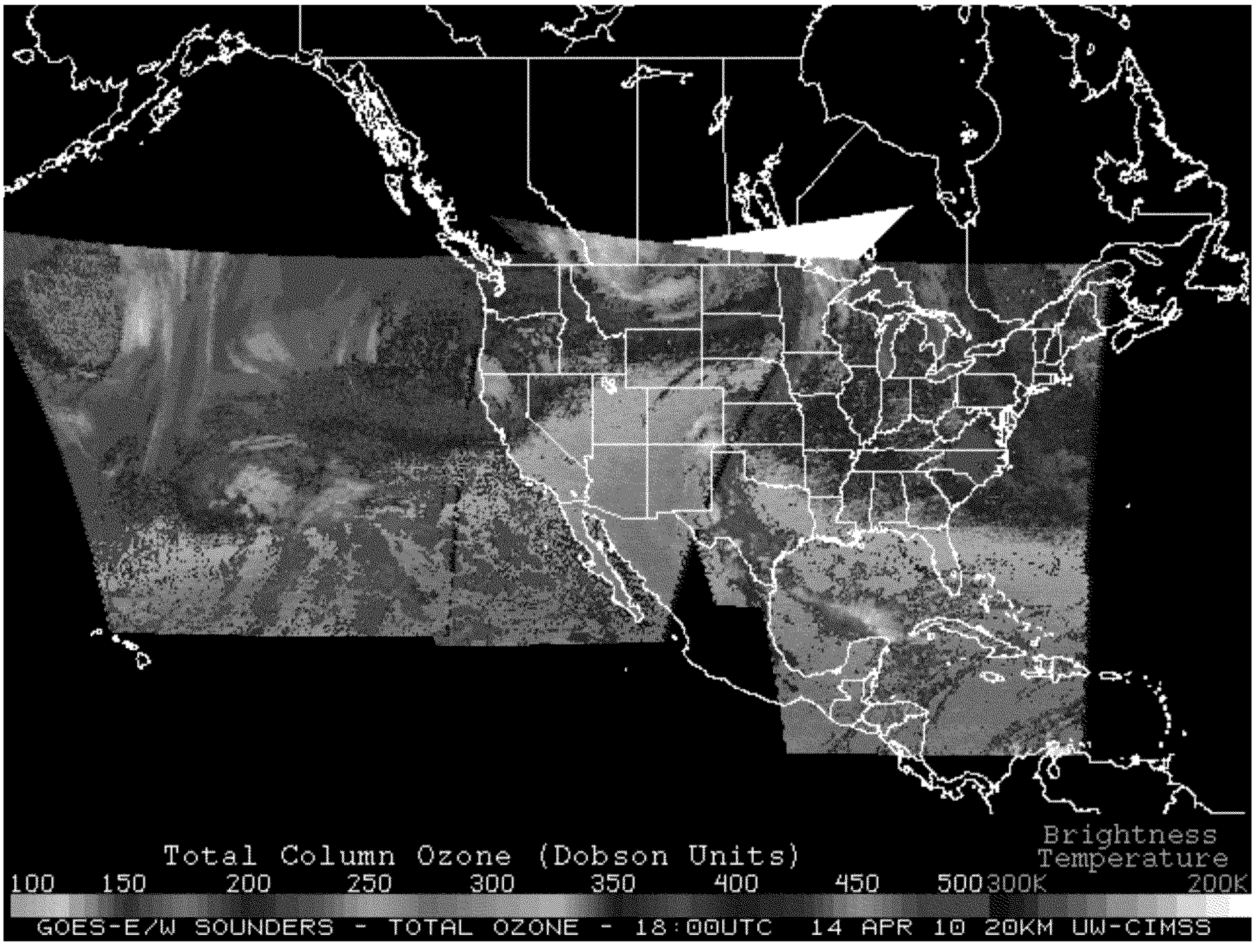

Figure 3. Total column ozone in DU at 1800 GMT April 14, 2010, derived from GOES satellite data (https://cimss.ssec.wisc.edu/goes/rt/viewdata.php?product=o3_us).

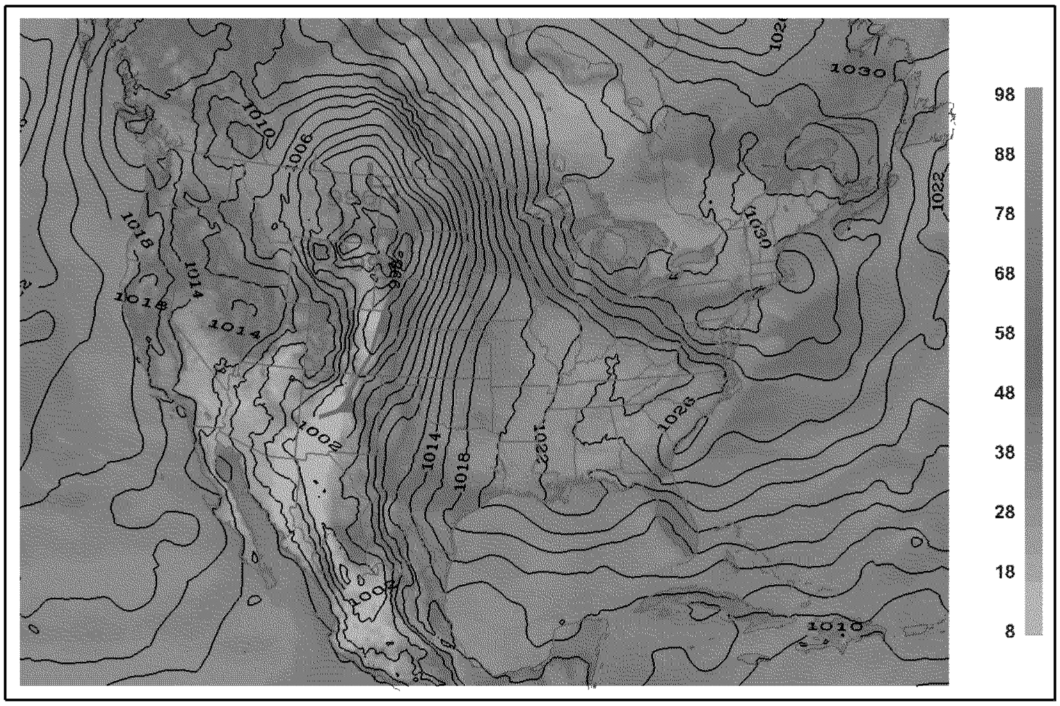

Figure 4. Mean seal-level pressure contours and relative humidity in percent (right scale) at 14:00 MST on April 13, 2010, from the 18Z hour 3 analysis of the 18Z NAM12 model.

The flight of a weather balloon produces a record of atmospheric conditions as it climbs, and this record is called a sounding. Figures 5 and 6 show the Denver soundings for 0 GMT and 12 GMT April 14, 2010, respectively. These are the soundings for 5 PM MST on April 13 and 5 AM MST on April 14. Exceedingly dry air was present above 650 mb on the first sounding (dew points depicted by the left line were below detection levels for most of the sounding), and dew points below -35 C were present above 600 mb on the second sounding. In each sounding, the onset of this dry air in the vertical is matched by small inversions where the dryness begins. Both the dry air and inversions or stable layers aloft are diagnostic of intrusion events.

Figure 7 shows the 500 mb height contours, relative humidity values below 20% (in pink) at the 500 millibar level, IPV in PVU at 500 mb (rainbow scale), and mixing heights above ground that were between 4000 and 5000 meters from the NAM12 analysis run for 18Z April 13, 2010. This map shows the arc of an intrusion event running from Wyoming through Colorado into Arizona. The mixing heights when added to the lowest base elevation of about 1600 meter MSL along the Front Range yield mixing heights that were deep enough to allow mixing of dry air and high IPV at 500 mb (around 5600 meters above sea level on this day) to surface sites along the Front Range. IPV values of 1.5 to 4.0 PVU were prevalent over the Front Range, indicating the presence of stratospheric air at 500 mb. Dry stratospheric air is visible along the arc of the intrusion event in Figure 7 and at the surface along the Front Range in Figure 4.

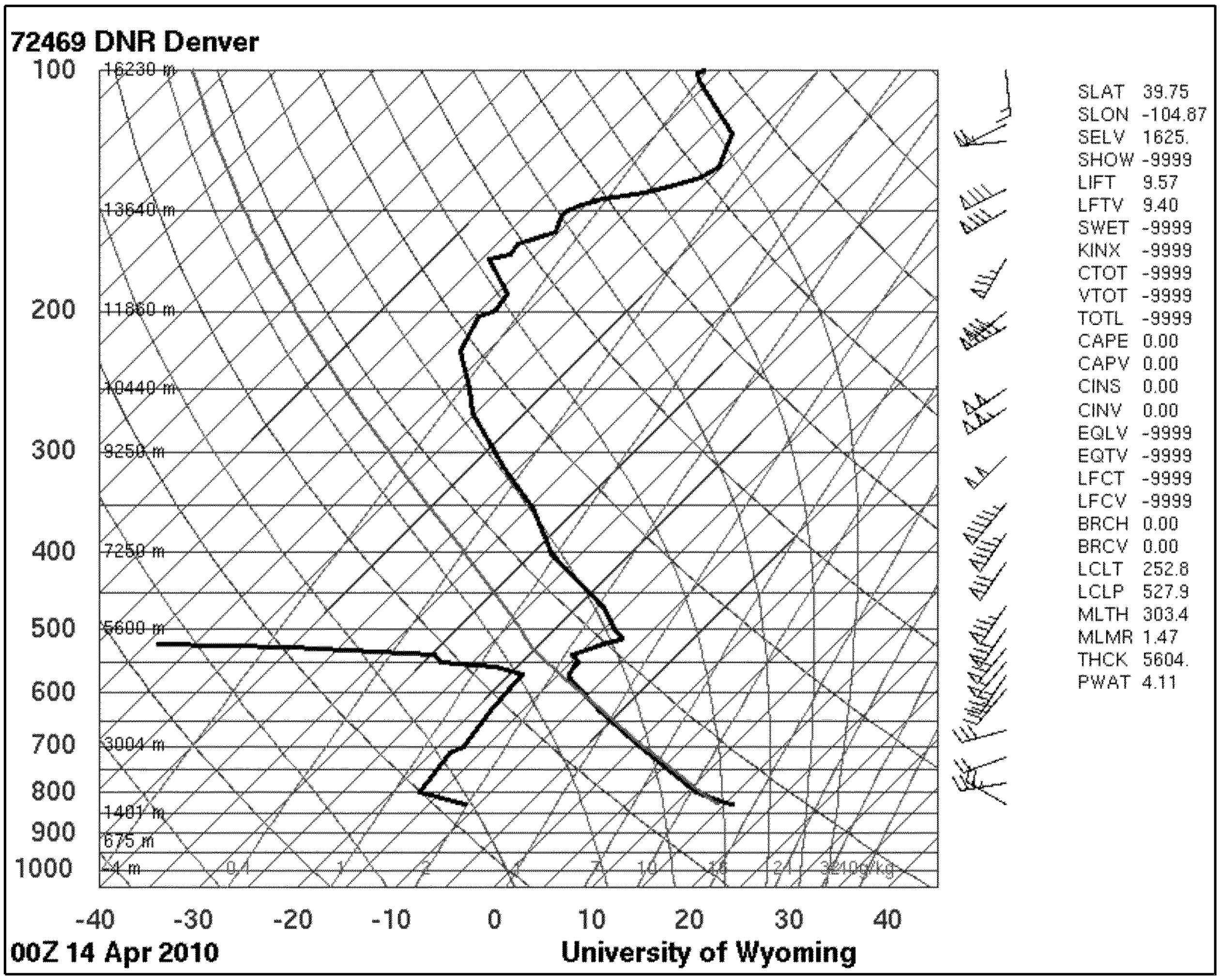

Figure 5. Denver sounding for 0 GMT April 14, 2010, from the University of Wyoming Department of Atmospheric Sciences (http://weather.uwyo.edu/upperair/sounding.html).

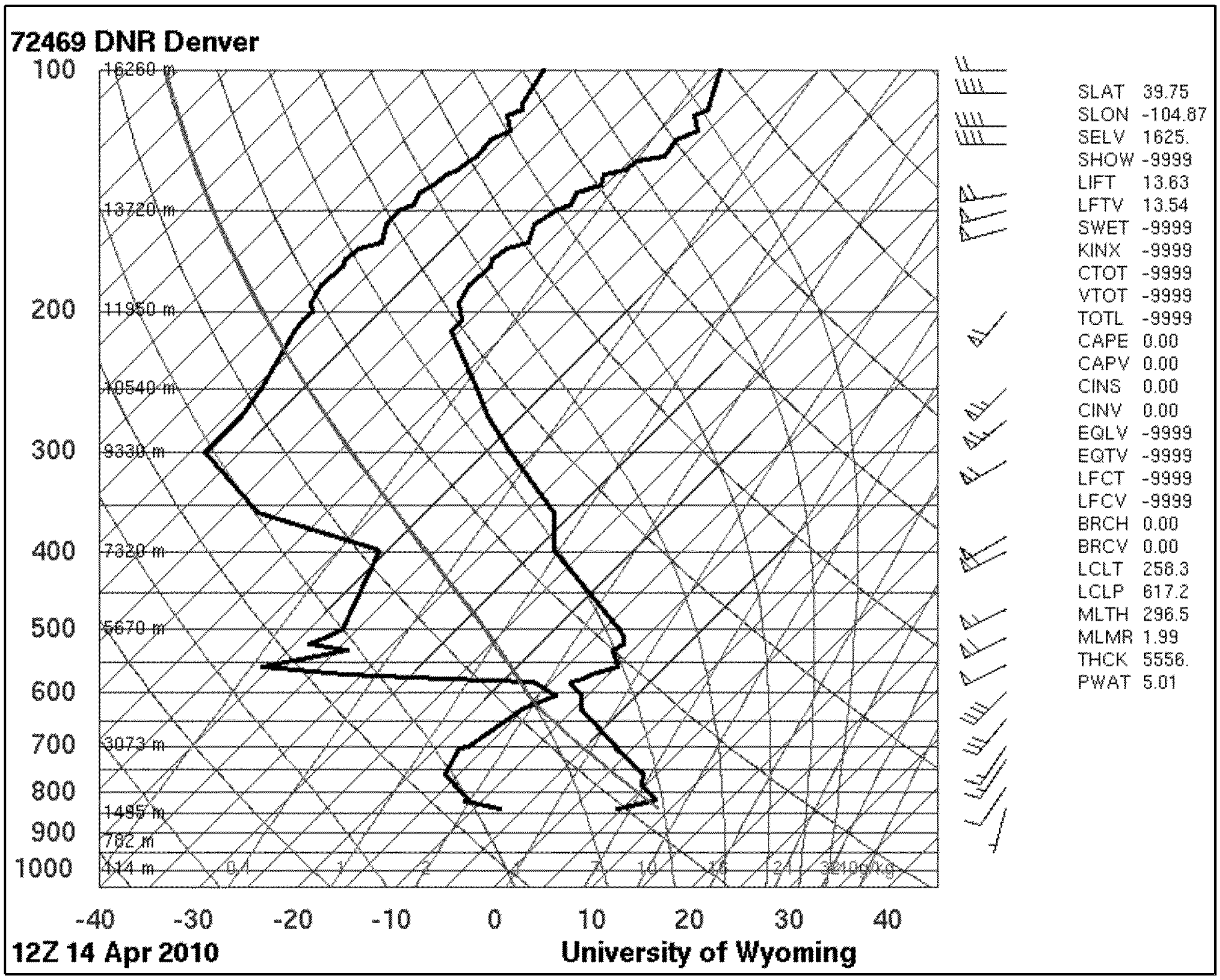

Figure 6. Denver sounding for 12 GMT April 14, 2010, from the University of Wyoming Department of Atmospheric Sciences (http://weather.uwyo.edu/upperair/sounding.html).

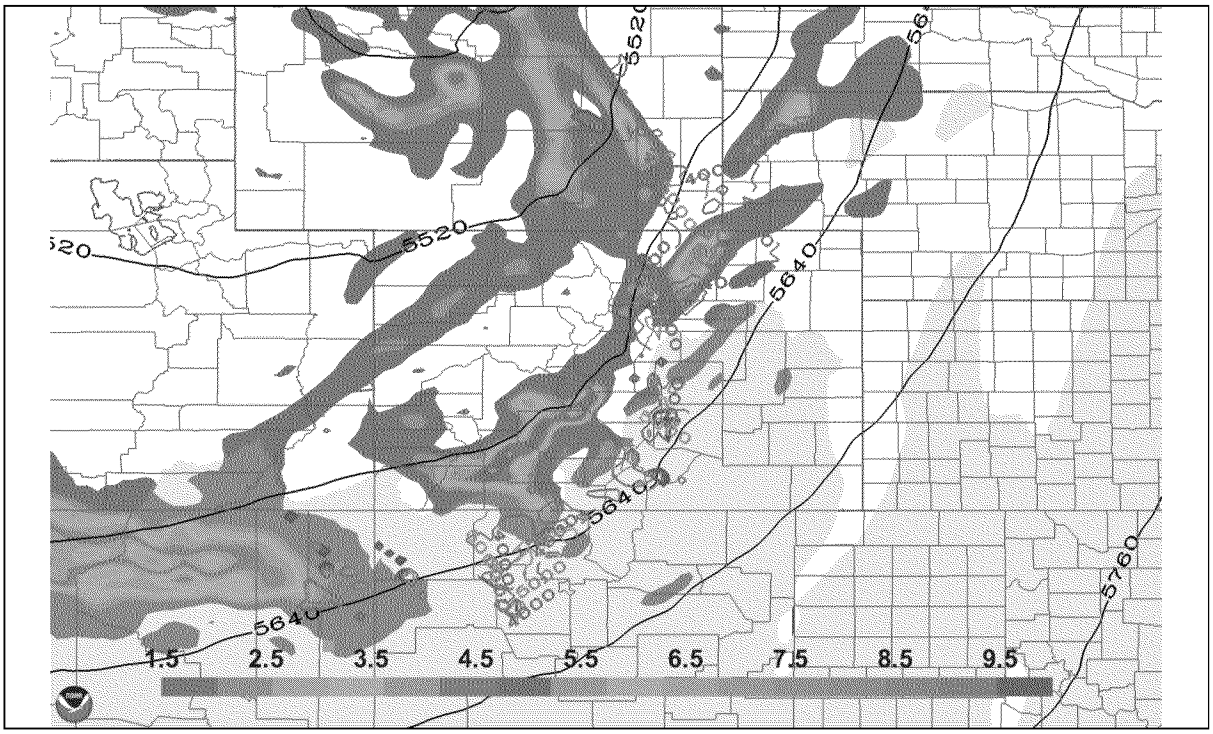

Figure 7. NAM12 analysis run for 18Z April 13, 2010, showing relative humidity below 20% in pink at 500 mb, IPV in PVUs above 1.5 according to rainbow scale at 500 mb, 500 mb heights in meters (black contours), and mixing height or planetary boundary layer heights of 4000 to 5000 meters above ground level in red and green contours.

Figures 8 and 9 show similar conditions on April 14, 2010. Figure 8 presents the 500 mb height contours, relative humidity values below 20% (in pink) at the 600 millibar level, and IPV in PVU at 600 mb (rainbow scale) from the NAM12 analysis run for 18Z April 14, 2010. Figure 9 shows where mixing heights above ground level exceeded 2000 meters. This map continues to show the arc of an intrusion event running through Colorado. The mixing heights when added to the lowest base elevation of about 1600 meter MSL along the Front Range yield mixing heights that were likely deep enough to allow mixing of dry air and high IPV at 600 mb (around 4300 meters above sea level on this day) to surface sites along the Front Range. IPV values of 1.5 to 4.0 PVU were prevalent over the Front Range, indicating the presence of stratospheric air at 600 mb. The features on this map are consistent with enhanced folding of the tropopause in the lee of the Front Range mountains and foothills.

Figure 10 shows one-hour ozone concentrations in ppb for Denver-Boulder area monitors: South Boulder Creek (SBC), Carriage (CRG), DMAS, Chatfield (CHAT), Arvada (ARV), and Welch (WCH). Peak afternoon ozone at CHAT was 87 ppb, which is anomalously high for April. Figure 11 shows one-hour ozone at a wider range of Front Range sites on April 13 and 14. These sites are: Aurora East (AURE), Air Force Academy (AFA), Manitou Springs (MAN), Rocky Flats (RFLAT), Aspen Park (ASP), Rocky Mountain National Park (RMNP), and Fort Collins West (FTCW). FTCW saw one hour peak values of 83 and 81 ppb on April 13 and 14, respectively, and these are anomalously high for April.

The presence of dry air with high IPV values, elevated total column ozone within the upper-level low, and unusually high concentrations for April are all diagnostic of an intrusion event. But for the stratospheric intrusion event, the high concentrations at CHAT and FTCW during this two-day event would not have occurred.

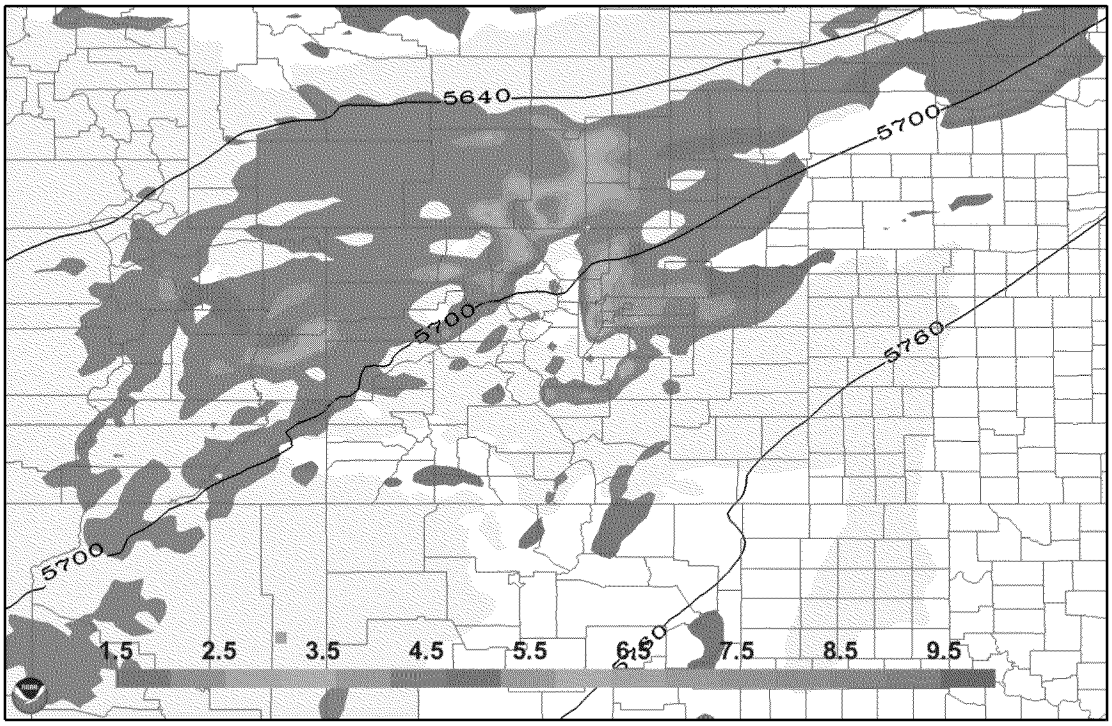

Figure 8. NAM12 analysis run for 18Z April 14, 2010, showing relative humidity below 20% in pink at 600 mb, IPV in PVUs above 1.5 according to rainbow scale at 600 mb, and 500 mb heights in meters (black contours).

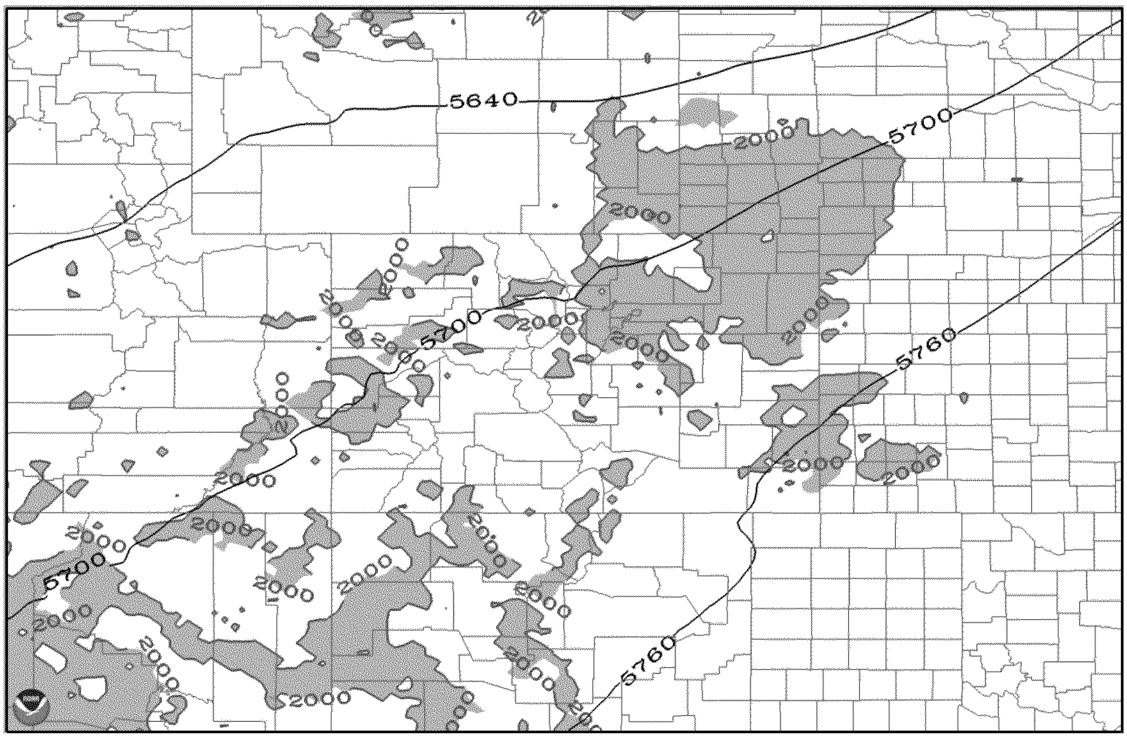

Figure 9. NAM12 analysis run for 18Z April 14, 2010, showing mixing heights or planetary boundary layer heights greater than 2000 meters above ground level in yellow.

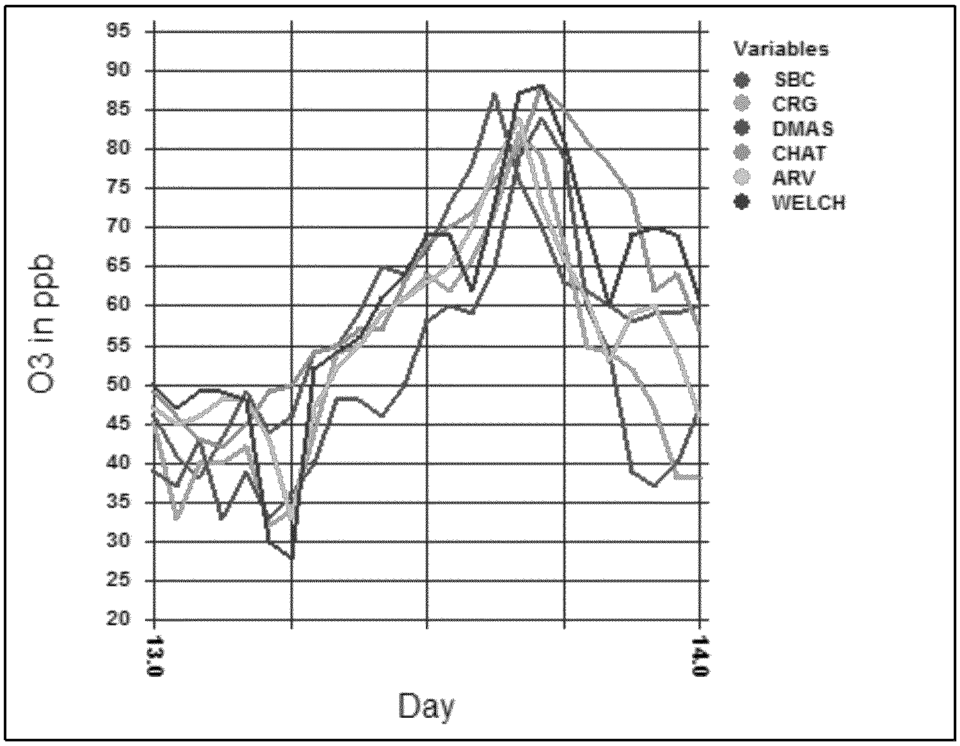

Figure 10. One-hour ozone concentrations in ppb at Denver-Boulder area monitors on April 13, 2010, in MST.

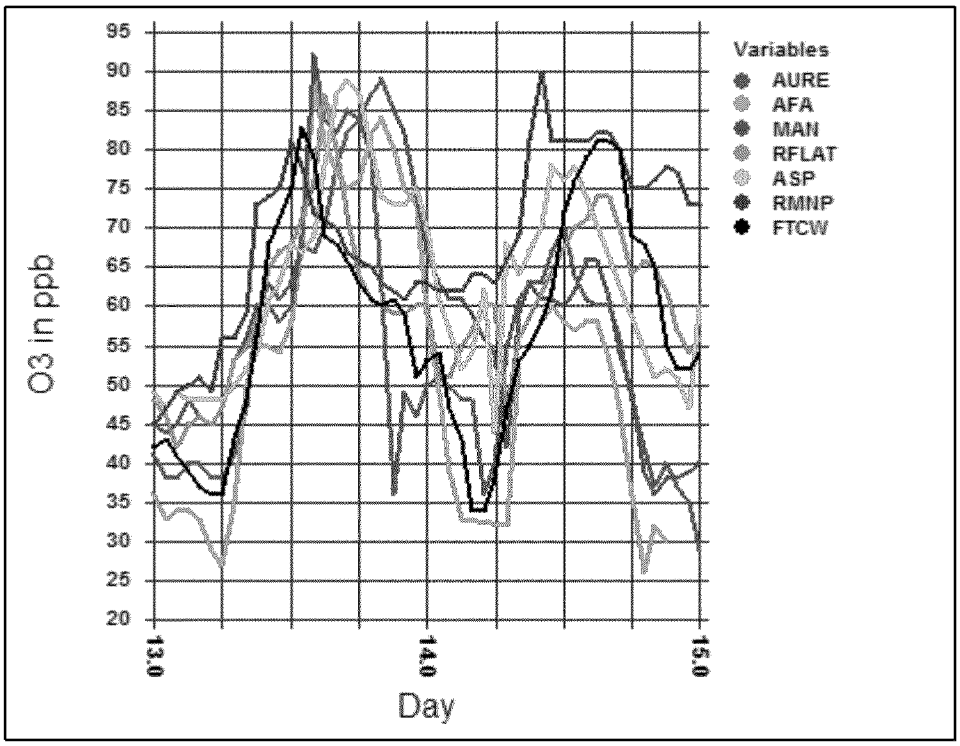

Figure 11. One-hour ozone concentrations in ppb at Front Range monitors on April 13 & 14, 2010, in MST.

The third stratospheric intrusion event from Table 1 occurred on June 7, 2011, and it led to a maximum 8-hour concentration of 84 ppb at CHAT, and this value was excluded from base year design value calculations in a SIP Weight of Evidence Analysis. The June 7 intrusion event in Colorado was caused by a strong and complex late spring storm with 500 millibar (mb) upper-level low centers of 5640 meters over Montana and 5700 meters over northern California (see Figure 12). Figure 12 is based on the 06 GMT analysis run of the NAM12 (available at: http://nomads.ncdc.noaa.gov/). Figure 12 also shows dry air (relative humidity values of 20% or less) plotted in pink for the 600 mb level and wind vectors at 500 mb. Strong southwesterly winds aloft covered Colorado. Figure 13 shows the total column ozone in DU for about 1330 MST on June 7, 2011. This is based on measurements from the Ozone Monitoring Instrument (OMI) onboard the Aura satellite. The OMI data plotted is level III version 3 data (Veefkind, 2012) from the NASA Goddard Earth Sciences Data and Information Services Center Giovanni website (Acker and Leptoukh, 2007, http://giovanni.gsfc.nasa.gov/giovanni/). Figure 13 shows high total column amounts of 300 to 350 DU over Colorado, Wyoming, Utah and other western states and a general pattern of high column ozone associated with the upper low system. The surface winds and surface humidity values of 20% or less are presented in Figure 14. The data in Figure 14 are from the 18 GMT run of the North American Regional Reanalysis or NARR (Mesinger et al., 2006) (data available at: http://nomads.ncdc.noaa.gov/). In this analysis, downslope winds of 5 to 15 knots were prevalent across the Front Range, and these downslope winds during the day do not fit the conceptual model for high ozone concentration conditions that are typically associated with pronounced thermally-driven upslope flow (Reddy and Pfister, 2016).

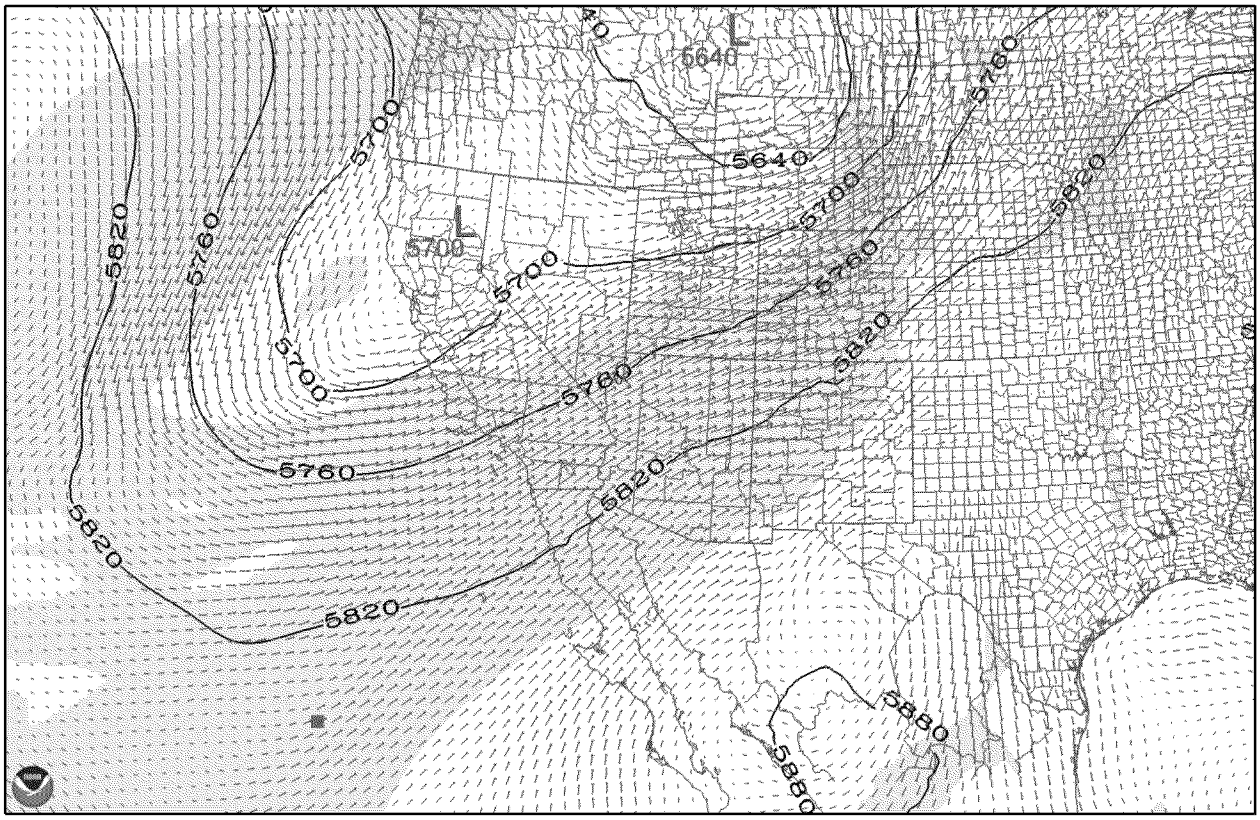

Figure 12. 500 mb heights in meters and wind vectors; relative humidity values of 20% or less at 600 mb in pink - from the 06Z analysis run of the NAM12 model for June 7, 2011.

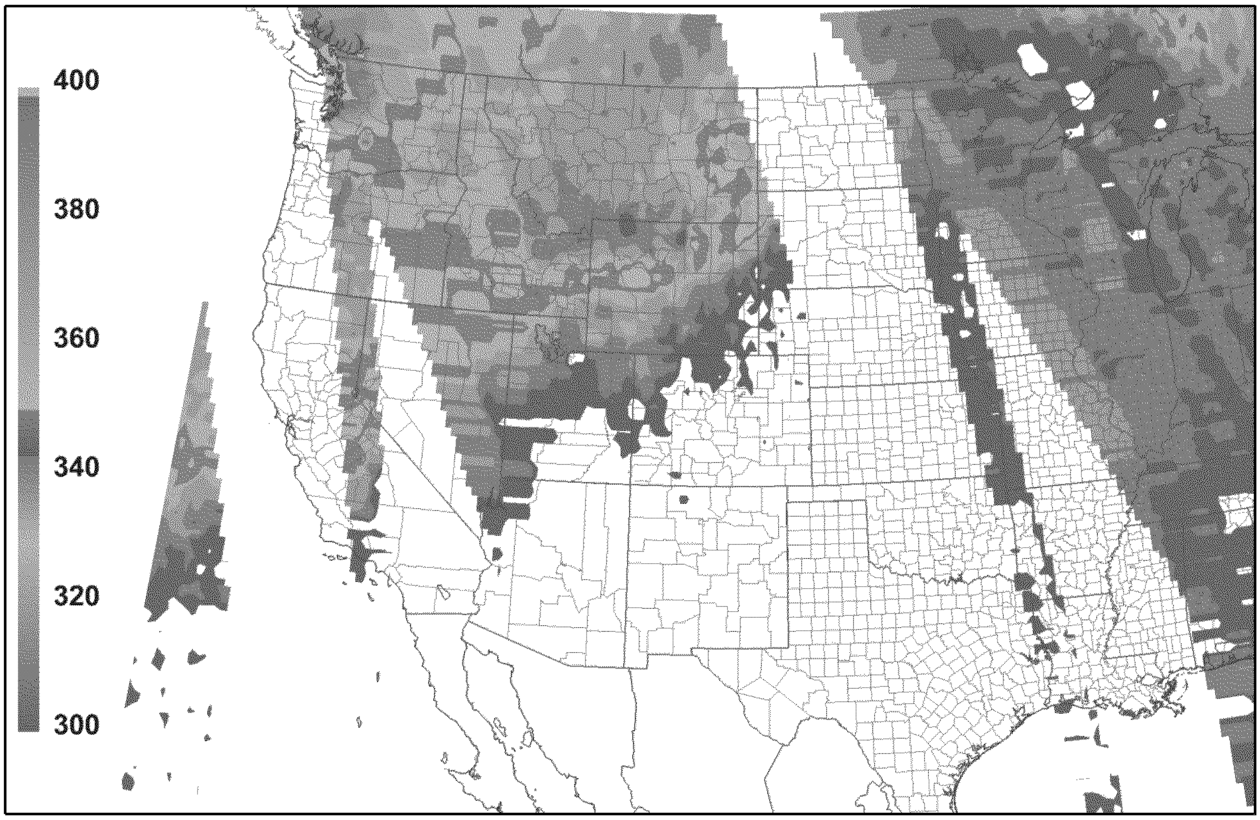

Figure 13. OMI level III version 3 total column ozone in DU for June 7, 2011, at approximately 1330 MST.

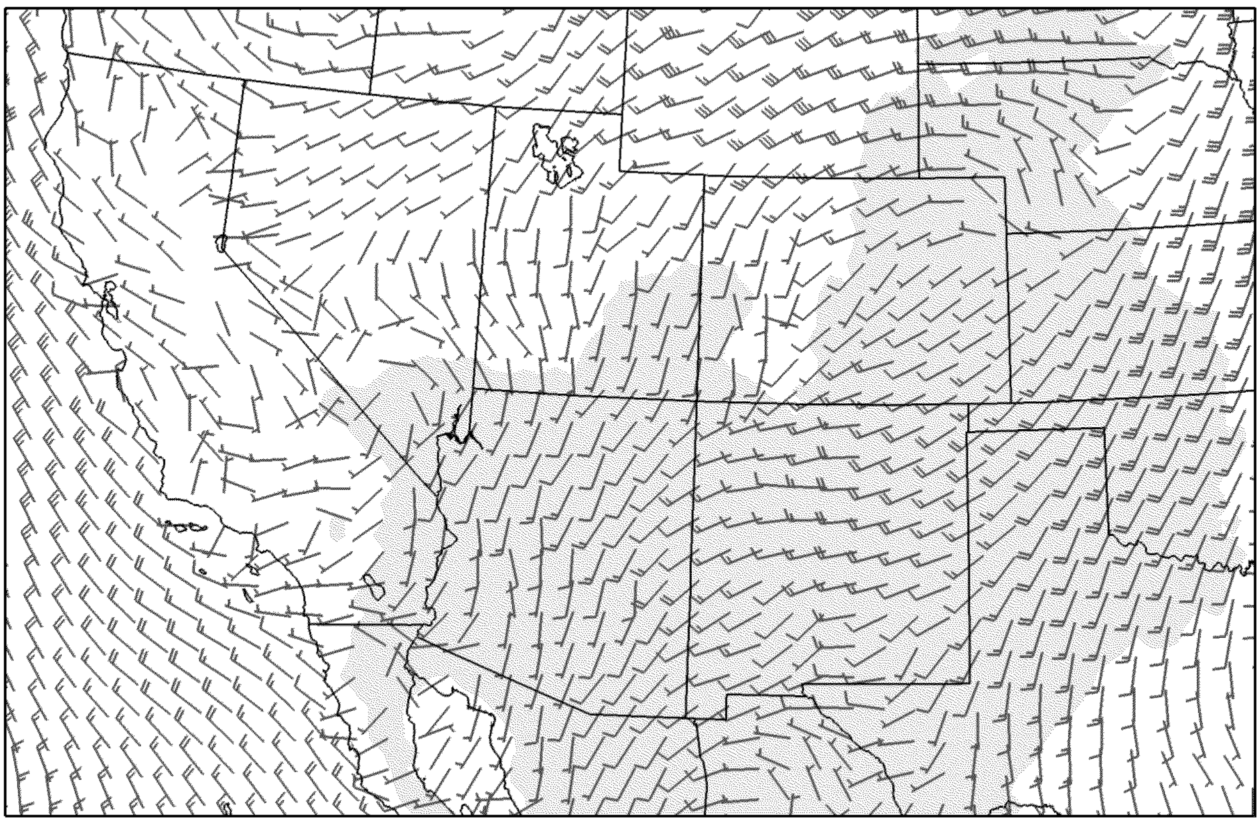
Figure 14. Surface winds in knots and surface relative humidity of 20% or less from the 18Z NARR for June7, 2011.

Figure 15 shows the Denver soundings for 12 GMT June 7, 2011. This is the soundings for 5 AM MST. Exceedingly dry air was present above 650 mb with dew points below -34. The onset of this dry air in the vertical is matched by a small inversion where the dryness begins. Both the dry air and inversion or stable layer aloft are diagnostic of intrusion events.

Figure 16 presents the NARR analysis run for 12Z June 7, 2011, (available at: http://nomads.ncdc.noaa.gov/) showing relative humidity below 20% in pink at 600 mb, IPV in PVUs above 1.5 at 600 mb, and 500 mb heights in meters (black contours). The patterns of high IPV show streamers or filaments of stratospheric air in the Front Range region, and these coincide with dry air at the same level. These patterns are indicative of an intrusion event.

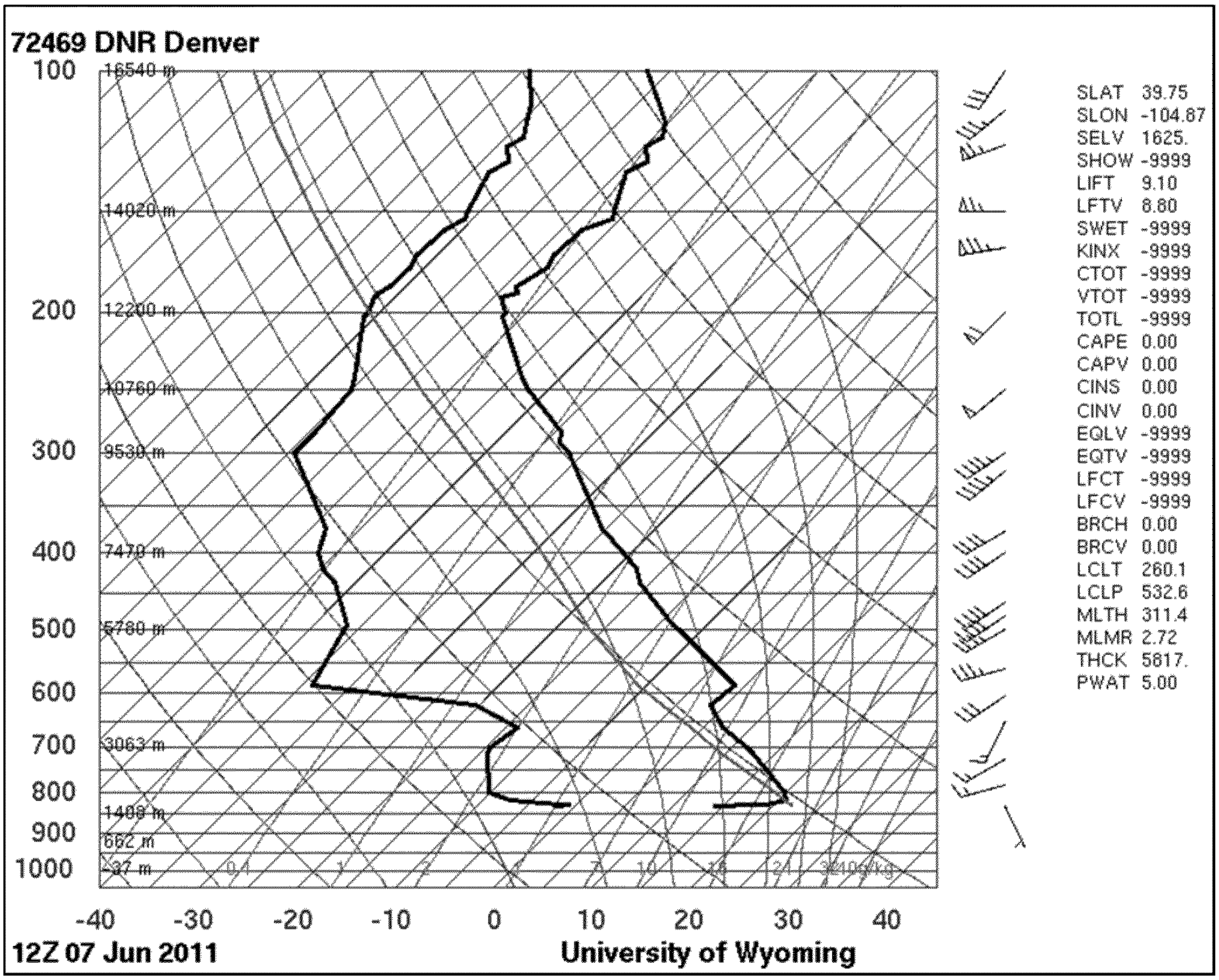

Figure 15. Denver sounding for 12 GMT June 7, 2011, from the University of Wyoming Department of Atmospheric Sciences (http://weather.uwyo.edu/upperair/sounding.html).

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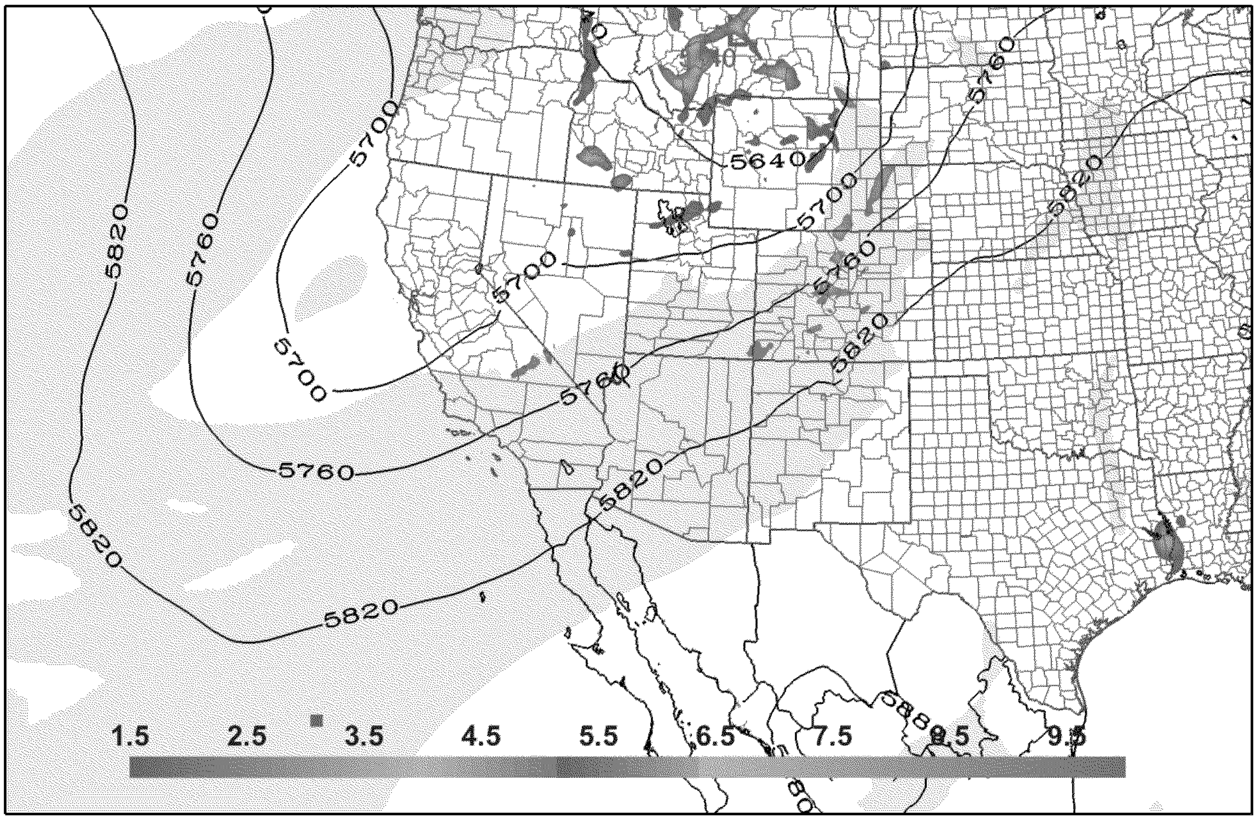

Figure 16. NARR analysis run for 12Z June 7, 2011, showing relative humidity below 20% in pink at 600 mb, IPV in PVUs above 1.5 according to rainbow scale at 600 mb, and 500 mb heights in meters (black contours).

Figure 17 shows the one-hour ozone concentrations in ppb for select Front Range monitors on June 7, 2011 (ASP, CHAT, FTCW, MAN, and RMNP). RMNP concentrations climb to between 68 and 75 ppb between 5 AM and 8 AM MST, and then level off at around 64 to 68 ppb for much of the day. ASP climbs to between 70 and 81 ppb between 9 AM and 11 AM MST. For each of these two foothill sites, the climb to high concentrations occurs earlier than typical for a summer high-concentration event. CHAT rises above 80 ppb at the hour beginning at 10 AM MST and stays above 80 ppb through the hour beginning at 5 PM MST. Figure 18 shows the wind directions at ASP and CHAT. Wind directions are downslope for most of the day at ASP and for the first part of the high-concentration event at CHAT. This is not typical for high-ozone events in this region (Reddy and Pfister, 2016).

The presence of dry air with high IPV values, elevated total column ozone within the upper-level low, and the prevalence of downslope winds are all diagnostic of an intrusion event. But for the stratospheric intrusion event, the high concentrations at CHAT during this event would not have occurred.

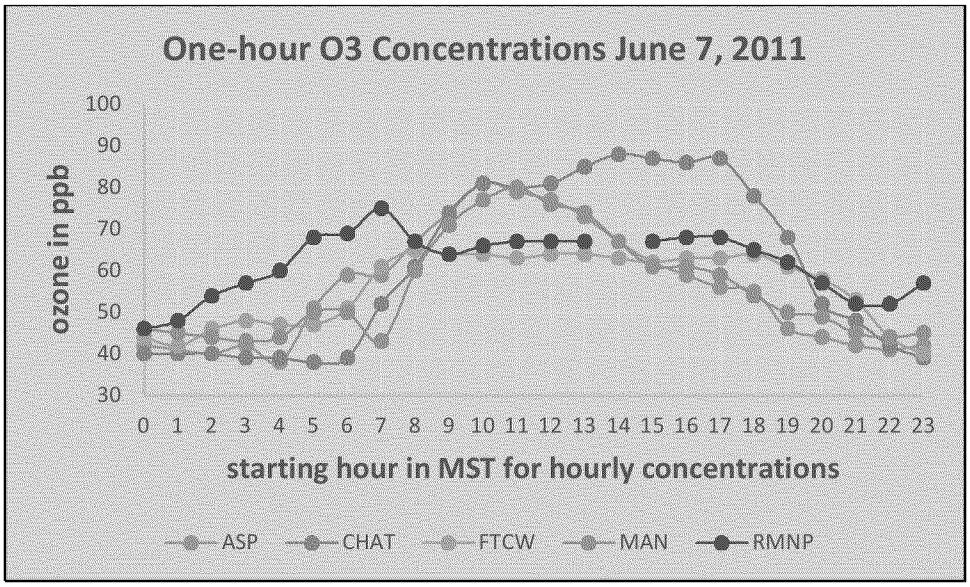

Figure 17. One-hour ozone concentrations in ppb for select Front Range monitors on June 7, 2011.

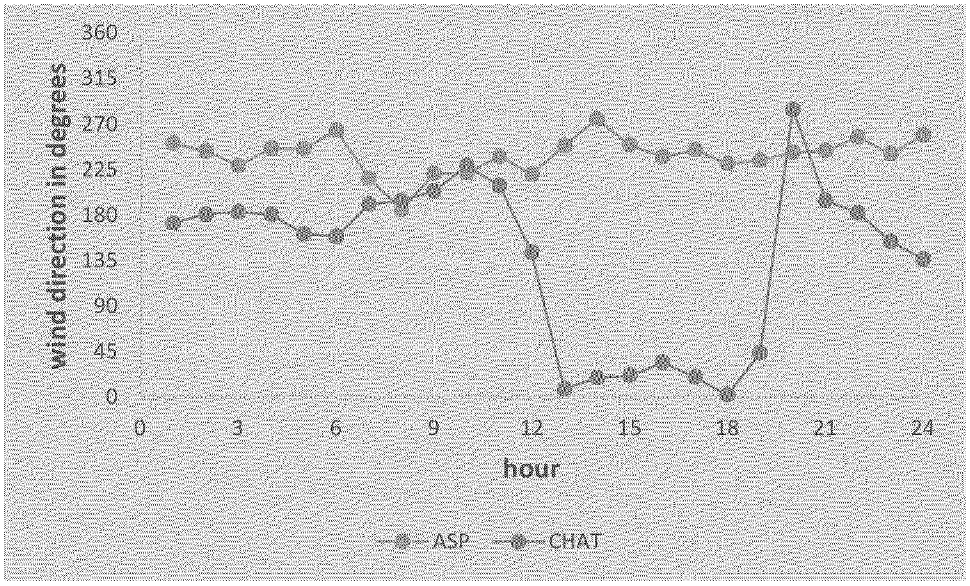

Figure 18. Wind directions in degrees for ASP and CHAT on June 7, 2011.

3.0 Wildfire Smoke Events in 2012 and 2013.

Smoke from wildfires can cause increases in ozone because of the emissions of NO_x and VOCs. Both the increased ozone and the precursor emissions from the region of a fire can be transported long distances. The relationships between smoke and ozone are complex (Jaffe and Widger, 2012). In some cases, smoke can lead to decreases in ozone. In general, high concentrations of ozone in the presence of smoke are candidates for flagging as exceptional events. The Colorado Department of Public Health and Environment used a variety of data sources to determine if a high concentration event was likely caused by or significantly influenced by wildfire smoke. These include satellite data and the results of a regression tool designed to highlight the likelihood that the ozone concentrations were higher than expected based on the meteorological conditions alone.

This regression method and data sources are discussed in detail in a paper by Jaffe et al. (2013). CDPHE applied this method for flagging of most of the smoke events in Table 1. CDPHE also selected meteorological variables based on the research described by Reddy and Pfister (2016) and a 2013 CDPHE whitepaper on ozone regression forecast modeling at:

http://www.colorado.gov/airquality/repository/mmei_file.aspx?file=framework+for+regression3.docx.

This method was applied for events in 2012, but the specific meteorological files needed for 2013 were not available.

Linear regression models which predict what ozone should have been based on meteorology were developed for Greeley, Fort Collins West, and Rocky Flats using daily mean meteorological data from the NCEP/NCAR reanalysis (Kalnay et al. 1996) for the Denver grid (see Reddy and Pfister, 2016) and daily max 8-hour ozone for January 1, 2002, through August 31, 2012. Model performance was improved by defining a cool season characterized by 500 mb heights less than or equal to 5810 meters and a warm season characterized by 500 mb heights above 5810 meters. The best variables for each site were selected with the aid of a variable selection algorithm.

The cool season model for Fort Collins West is as follows:

Predicted daily 8-hour maximum ozone = 396.106+ .928028*2mtemp+ .356341*2mtempled-.031480*500ht-.152376*500roll30prior+ .042893*500roll30-3130.32*600sphumanom+ 1.65908322133499*700temproll30

Where 2mtemp is the daily mean temperature in degrees C, 2mtempled is tomorrow's daily mean temperature in degrees C, 500ht is the 500 mb height in meters, 500roll30prior is the rolling 30-day average 500 mb heights in meters ending on the day of interest, 500roll30 is the rolling 30-day average 500 mb heights in meters centered on the day of interest, 600sphumanom is the 600 mb specific humidity anomaly in kg/kg, and 700temproll30 is the rolling 30-day average 700 mb temperature in degrees C ending on the day of interest.

The cool season model for Greeley is as follows:

663.915+ 1.69255*2mtemp+ .202179*2mtempled-.038596*500hts-.241617*500roll30prior+ .038444*500roll30-3128.55*600sphumanom-.590214*700temp+ 3.35182*700temproll30

Where the variables used have been described above and 700temp is the mean 700 mb temperature in degrees C.

The cool season model for Rocky Flats is as follows:

448.068+ .858661*2mtemp+ .532923*2mtempled-.030374*500hts-.146097*500roll30prior+ .033972*500roll30-3994.60*600sphumanom+ 1.50196*700temproll30

Where the variables used have been described above.

The warm season model for Fort Collins West is as follows:

Predicted daily 8-hour maximum ozone = -209.616+ .704053*2mtemp+ 1.07061*2mtempled+ .067327*500roll30-1907.247*600sphumanom-.508404*700temp

Where the variables used have been described above.

The warm season model for Greeley is as follows:

Predicted daily 8-hour maximum ozone = -68.7141+ 1.21595*2mtemp+ .876336*2mtempled-.0307160*500roll30prior+ .086355*500roll30-1298.802*600sphumanom-.787567*700temp

Where the variables have been described above.

The warm season model for Rocky Flats is as follows:

Predicted daily 8-hour maximum ozone = -449.306+ .449325*2mtemp+ .900982*2mtempled+ .084365*500roll30-1436.95*600sphumanomroll30

Where the variables have the same definitions already described and 600sphumanomroll30 is the rolling 30-day average 600 mb specific humidity anomaly ending on the day of interest.

The cool season linear regression models for Fort Collins West, Greeley, and Rocky Flats have R-squared values of 0.59, 0.63, and 0.51, respectively. The warm season linear regression models for Fort Collins West, Greeley, and Rocky Flats have R-squared values of 0.46, 0.57, and 0.50, respectively. Data to support the flagging of the smoke events of 2012 and 2013 are presented below. These data sources include the NOAA Hazard Mapping and Smoke (HMS) analyzed smoke coverage maps from the HMS web site (http://www.ospo.noaa.gov/Products/land/hms.html) and the AirNow-Tech website (https://airnowtech.org), NOAA HYSPLIT back trajectories (Stein et al., 2015) from the AirNow-Tech website, and the ozone residuals (actual ozone minus predicted ozone) from the linear regression models just described. The HMS analyzed smoke plots from AirNow-Tech are the most recently available and not necessarily for the hour of interest. The smoke coverage patterns are generated by experts within the HMS program who interpret satellite products.

May 15, 2012

Smoke from the Hewlett Fire along the Front Range and smoke from long range transport affecting much of North America may have contributed to high concentrations at Fort Collins West on May 15. Ozone forecast regression models showed residuals of +16 ppb, +16 ppb, and +19 ppb at Rocky Flats North, Greeley, and Ft. Collins West, respectively. In other words, the models estimate anomalously high ozone at these sites, and these residuals reflect the estimated excess ozone that may be attributable to smoke. Figure 19 shows the HMS product for 1924 GMT or 1224 MST with analyzed smoke and fires. Smoke covers eastern Colorado. Figure 20 shows the AirNow-Tech map for 12 MST on May 15, 2012. Smoke from the Hewlett Fire and long range transport affected Front range area monitors. These data suggest that the 76 ppb daily max 8-hour ozone at Fort Collins West (Table 1) was heavily influenced by smoke-related ozone.

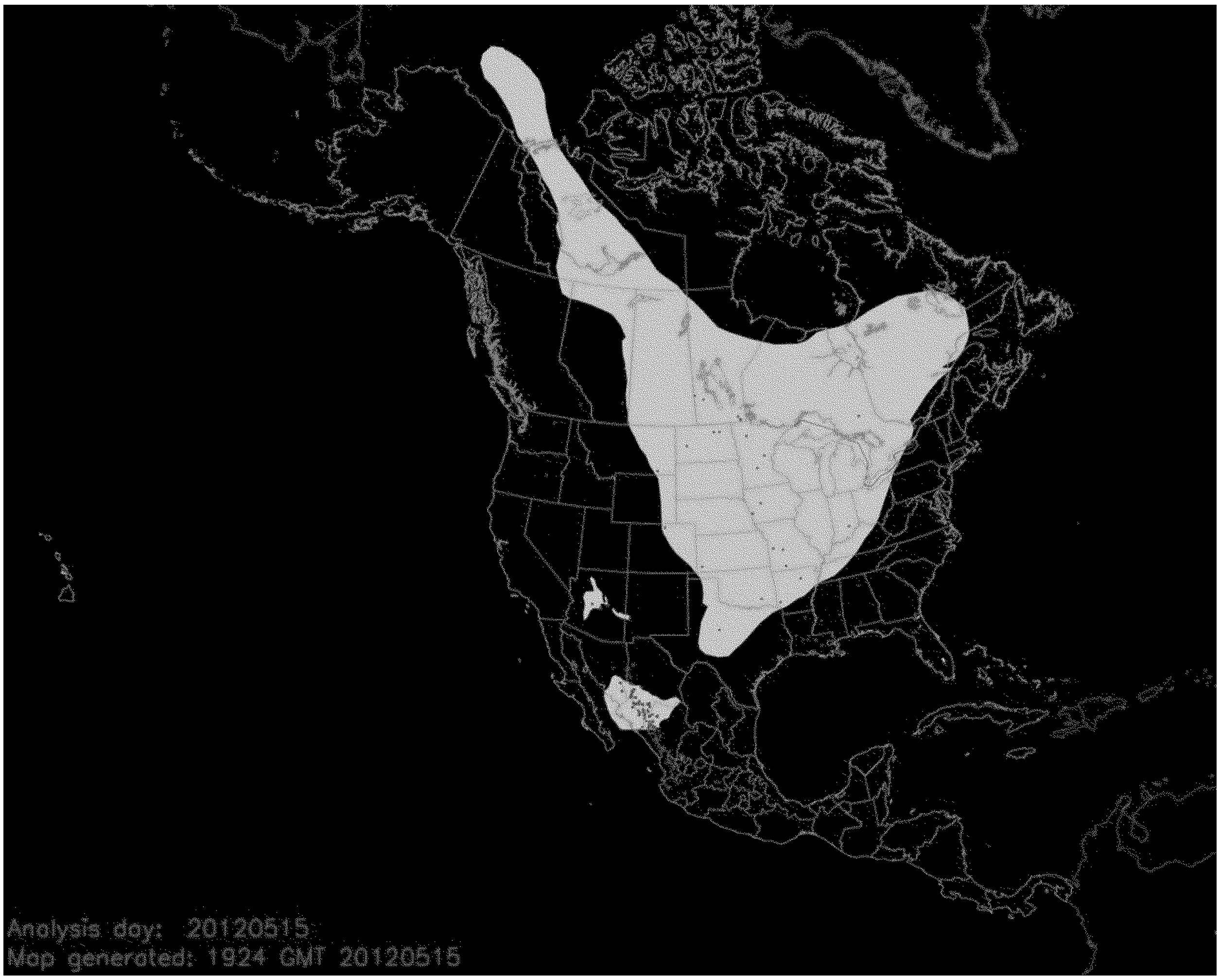

Figure 19. NOAA HMS smoke analysis for 1924 GMT, May 15, 2012. Smoke is in light gray, fires in red.

June 17, 2012

A smoke plume from the High Park Fire in Larimer County affected Weld and Larimer Counties (see Figure 21 for 12 MST). Ozone forecast regression models showed a 13 ppb positive residual at the Greeley Weld County Tower site and an 11 ppb positive residual at the Fort Collins West site. The residual at the Rocky Flats monitor which was not under the plume was only 3 ppb. These data suggest that the 77 ppb daily max 8-hour ozone at Fort Collins West (Table 1) was heavily influenced by smoke-related ozone.

June 22, 2012

A plume of smoke from the High Park Fire in Larimer County was entrained into an area of limited planetary boundary layer depth along the Northern Front Range from west of Denver northward (see figure 22 for 12 MST). Ozone forecast regression models showed a 25 ppb positive residual at the Fort Collins West site and a 34 ppb positive residual at the at the Rocky Flats North site. These data suggest that the 101 ppb, 83 ppb, and 93 ppb daily max 8-hour ozone concentrations at Rocky Flats, NREL, and Fort Collins West, respectively, (Table 1) were heavily influenced by smoke-related ozone.

July 4, 2012

The composite AirNow-Tech products in Figures 23 and 24 for 12 MST show a large mass or plume of smoke from fires burning in Wyoming, Montana, and South Dakota (on July 3) entering northeastern Colorado behind a cool front that crossed into Colorado during the morning hours. The presence of smoke was also verified by one-hour surface PM2.5 concentrations of 60.8 ug/m^3 and 73.7 ug/m^3 at Greeley and Welby at 12 MST, respectively (see Figure 24). This smoke was trapped within the surface mixed layer from the Denver area north to the Wyoming border and east of the Front Range. Ozone forecast regression models showed positive residuals of 20 ppb, 20 ppb, and 9 ppb at Rocky Flats North, Weld County Tower, and Ft. Collins West, respectively. These data suggest that the 96 ppb, 92 ppb, 95 ppb, and 76 ppb daily max 8-hour ozone concentrations at Chatfield, Rocky Flats, NREL, and Fort Collins West, respectively, (Table 1) were heavily influenced by smoke-related ozone.

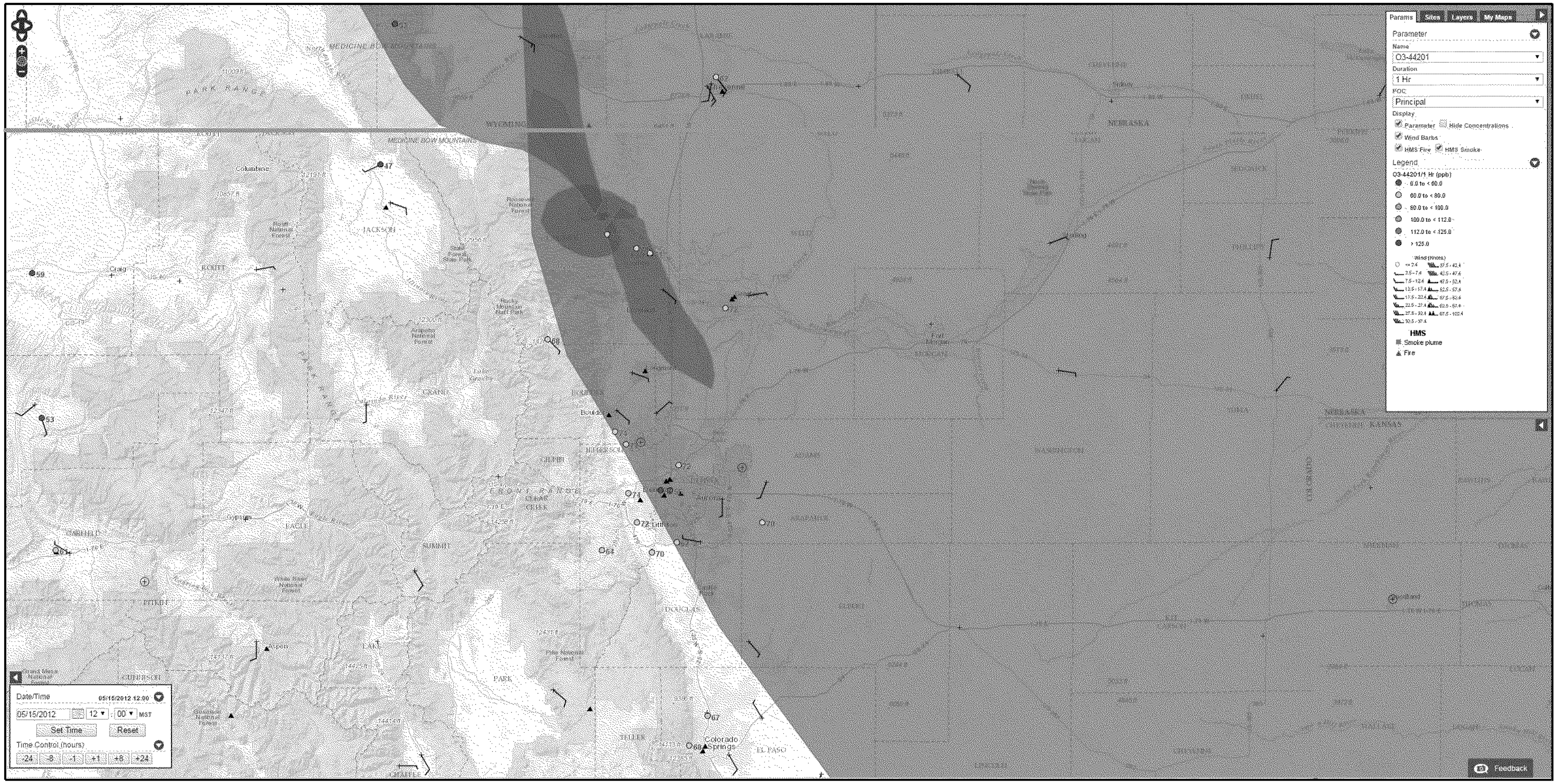

Figure 20. AirNow-Tech one-hour ozone concentrations, surface wind barbs, HMS fires in red, and most recent HMS analyzed smoke in gray for 12 MST May 15, 2012. Zoom in for a more detailed look. Colorado borders in blue.

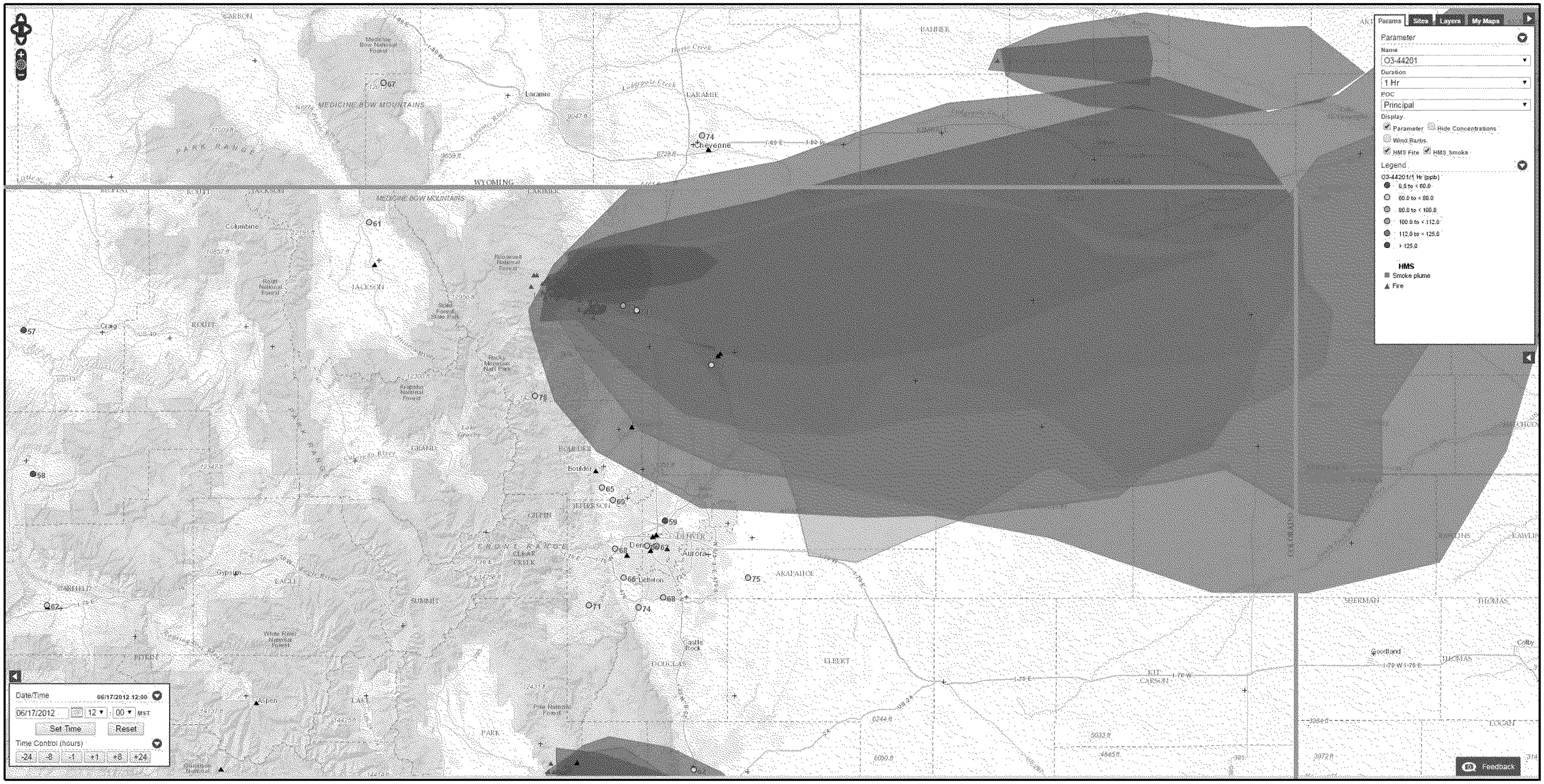

Figure 21. AirNow-Tech one-hour ozone concentrations, surface wind barbs, HMS fires in red, and most recent HMS analyzed smoke in gray for 12 MST June 17, 2012. Zoom in for a more detailed look. Colorado borders in blue.

Figure 22. AirNow-Tech one-hour ozone concentrations, surface wind barbs, HMS fires in red, and most recent HMS analyzed smoke in gray for 12 MST June 22, 2012. Zoom in for a more detailed look. Colorado borders in blue.

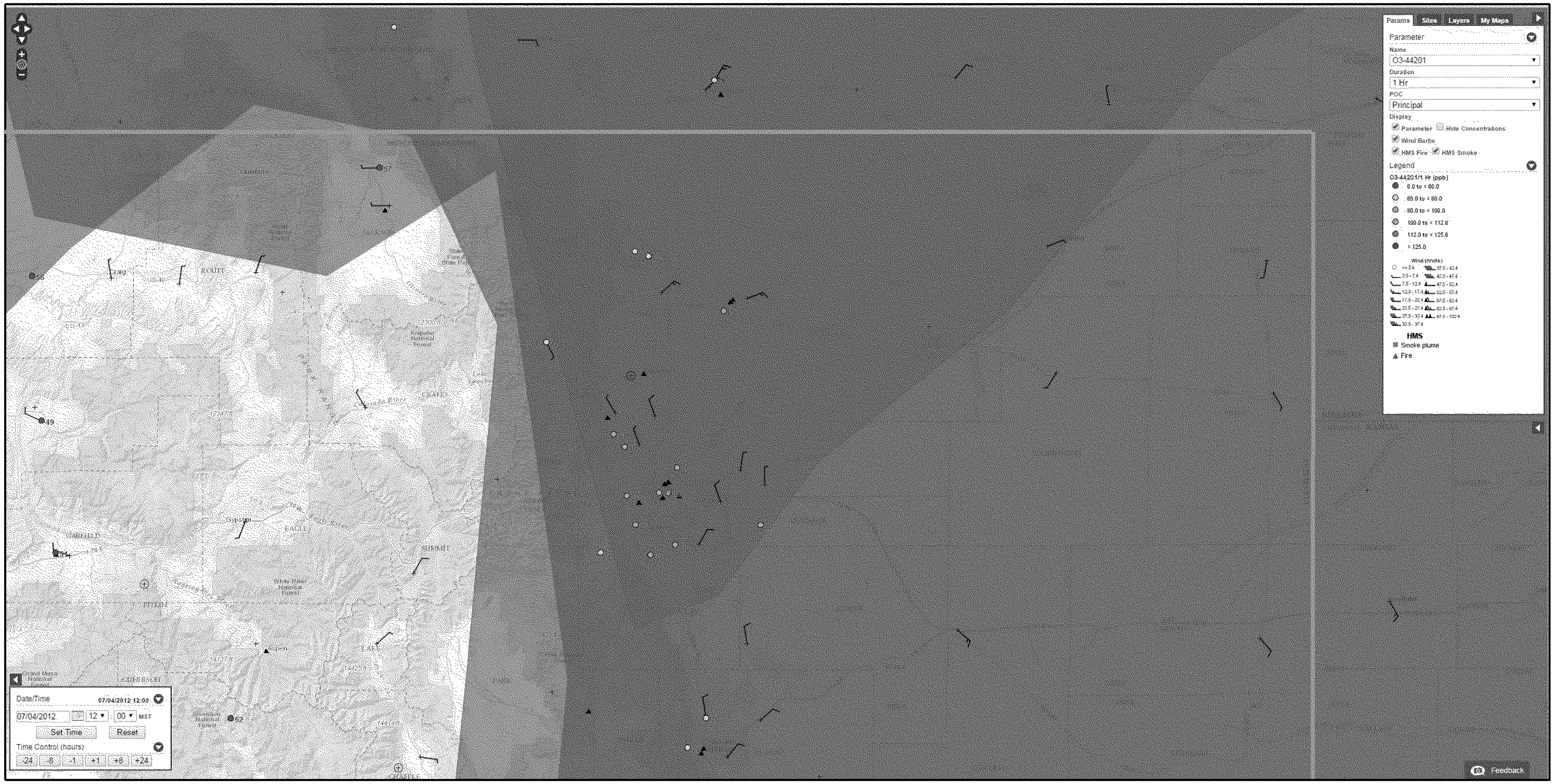

Figure 23. AirNow-Tech one-hour ozone concentrations, surface wind barbs, fires in red, and most recent HMS analyzed smoke in gray for 12 MST July 4, 2012. Zoom in for a more detailed look. Colorado borders in blue.

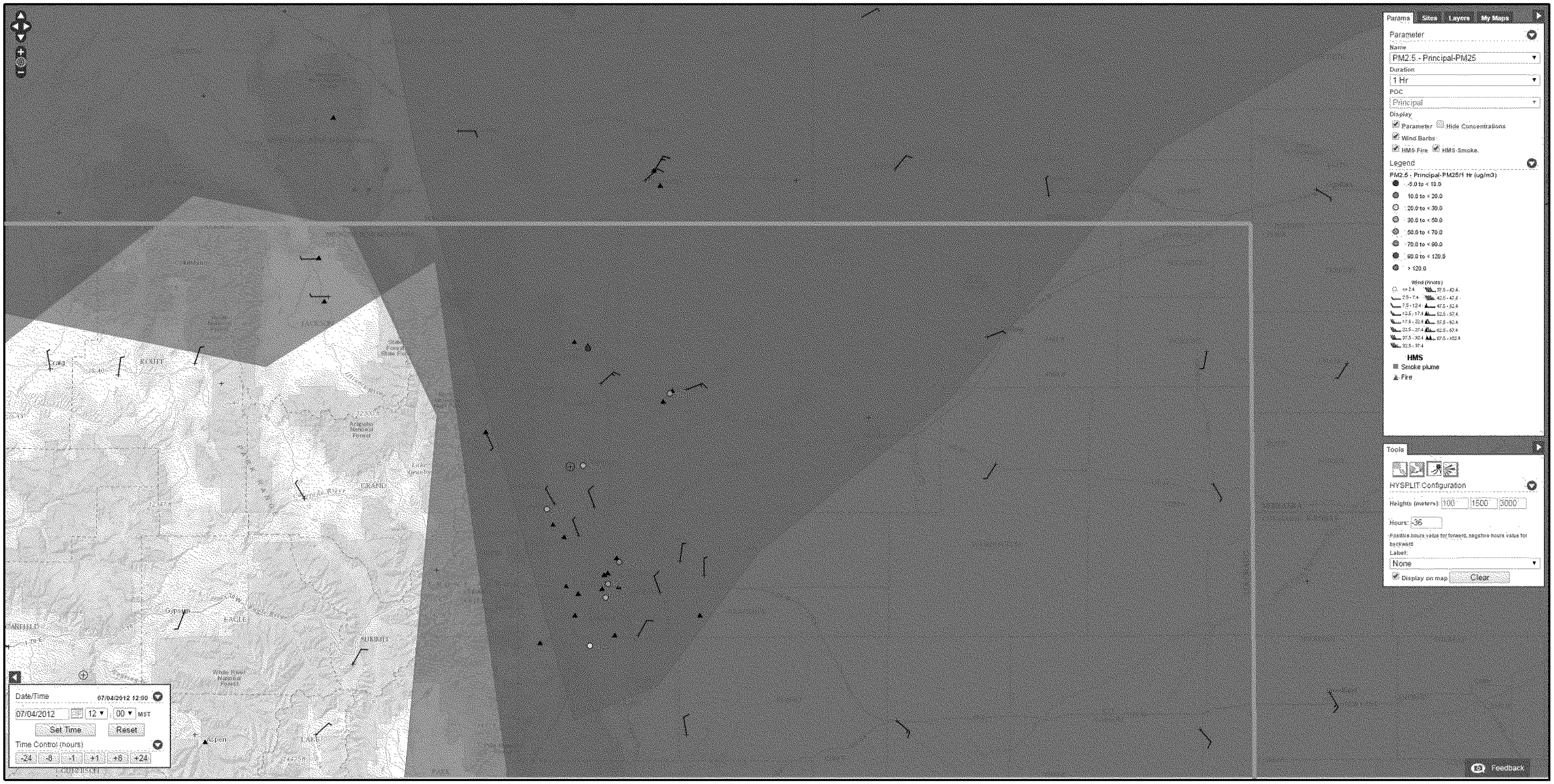

Figure 24. AirNow-Tech one-hour PM2.5 concentrations, surface wind barbs, fires in red, and most recent HMS analyzed smoke in gray for 12 MST July 4, 2012. Zoom in for a more detailed look. Colorado borders in blue.

July 5, 2012

The AirNow-Tech composite products in Figure 25 show that the smoke from Wyoming, Montana, and South Dakota that entered the region on July 4 continued across much of the Front Range region on July 5. Ozone forecast regression models showed positive residuals of 18 ppb, 3 ppb, and 13 ppb at Rocky Flats North, Greeley, and Ft. Collins West, respectively. These data suggest that the 88 ppb and 81 ppb daily max 8-hour ozone concentrations at Rocky Flats and NREL, respectively, (Table 1) were heavily influenced by smoke-related ozone.

August 9, 2012

The AirNow-Tech composite products in Figure 26 show that a large area of smoke from fires burning in Utah, Nevada, Idaho, Oregon, California, and Montana covered northern Colorado. Ozone forecast regression models showed positive residuals of 16 ppb, 5 ppb, and 16 ppb at Rocky Flats North, Greeley, and Ft. Collins West, respectively. These data suggest that the 98 ppb, 84 ppb, 88 ppb, and 86 ppb daily max 8-hour ozone concentrations at Chatfield, Rocky Flats, NREL, and Fort Collins West, respectively, (Table 1) were heavily influenced by smoke-related ozone.

August 21, 2012

The AirNow-Tech composite products in Figure 27 show an area of smoke from fires burning in western and northwestern states covering northeastern Colorado at 12 MST on August 21. Ozone forecast regression models showed residuals of +14 ppb, +1 ppb, and +4 ppb at Rocky Flats North, Greeley, and Ft. Collins West, respectively. These data suggest that the 80 ppb, 80 ppb, and 80 ppb daily max 8-hour ozone concentrations at Chatfield, Rocky Flats, and NREL, respectively, (Table 1) were heavily influenced by smoke-related ozone.

August 25, 2012

The AirNow-Tech composite products in Figure 28 show an extensive area of smoke at 12 MST on August 24 from fires burning in western and northwestern states. This map also shows the NOAA HYSPLIT 36-hour back trajectories (with an arrival height of 100 meters above ground) calculated for an arrival at monitors just west of Denver at 12 MST on August 25. These back trajectories show that ozone and/or its precursors from dense smoke in Montana and Wyoming was likely transported to the Front Range by August 25. Ozone forecast regression models showed residuals of +17 ppb, -5 ppb, and -1 ppb at Rocky Flats North, Greeley, and Ft. Collins West, respectively. These data suggest that the 80 ppb daily max 8-hour ozone concentrations at Rocky Flats (Table 1) was heavily influenced by smoke-related ozone. Figure 29 shows that the expert analyzed smoke pattern did not cover Colorado on the 25^{th}, but this does not rule out the transport of ozone and precursors that would not have been visible in the satellite products.

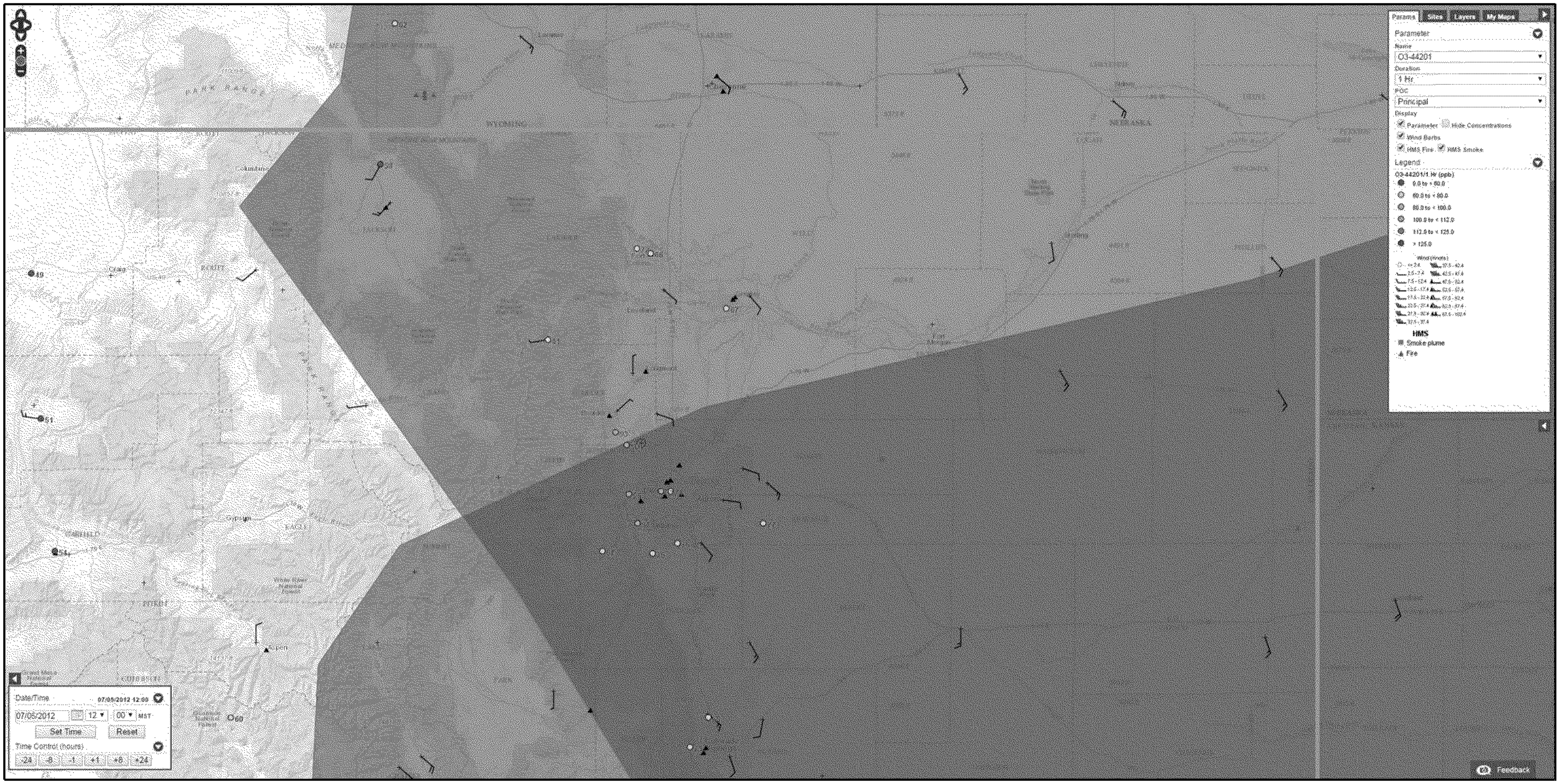

Figure 25. AirNow-Tech one-hour ozone concentrations, surface wind barbs, fires in red, and most recent HMS analyzed smoke in gray for 12 MST July 5, 2012. Zoom in for a more detailed look. Colorado borders in blue.

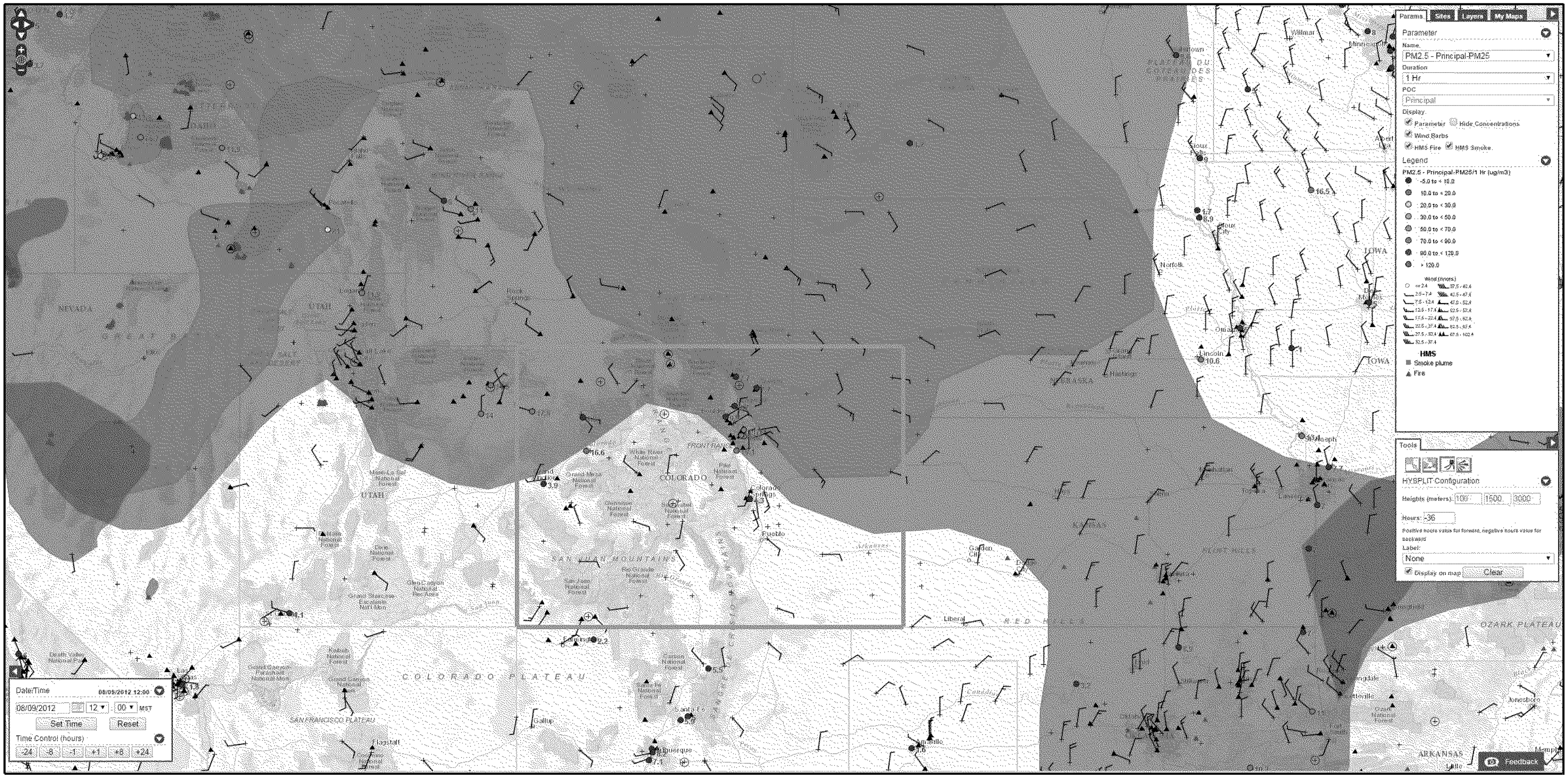

Figure 26. AirNow-Tech one-hour ozone concentrations, surface wind barbs, fires in red, and most recent HMS analyzed smoke in gray for 12 MST August 9, 2012. Zoom in for a more detailed look. Colorado borders in blue.

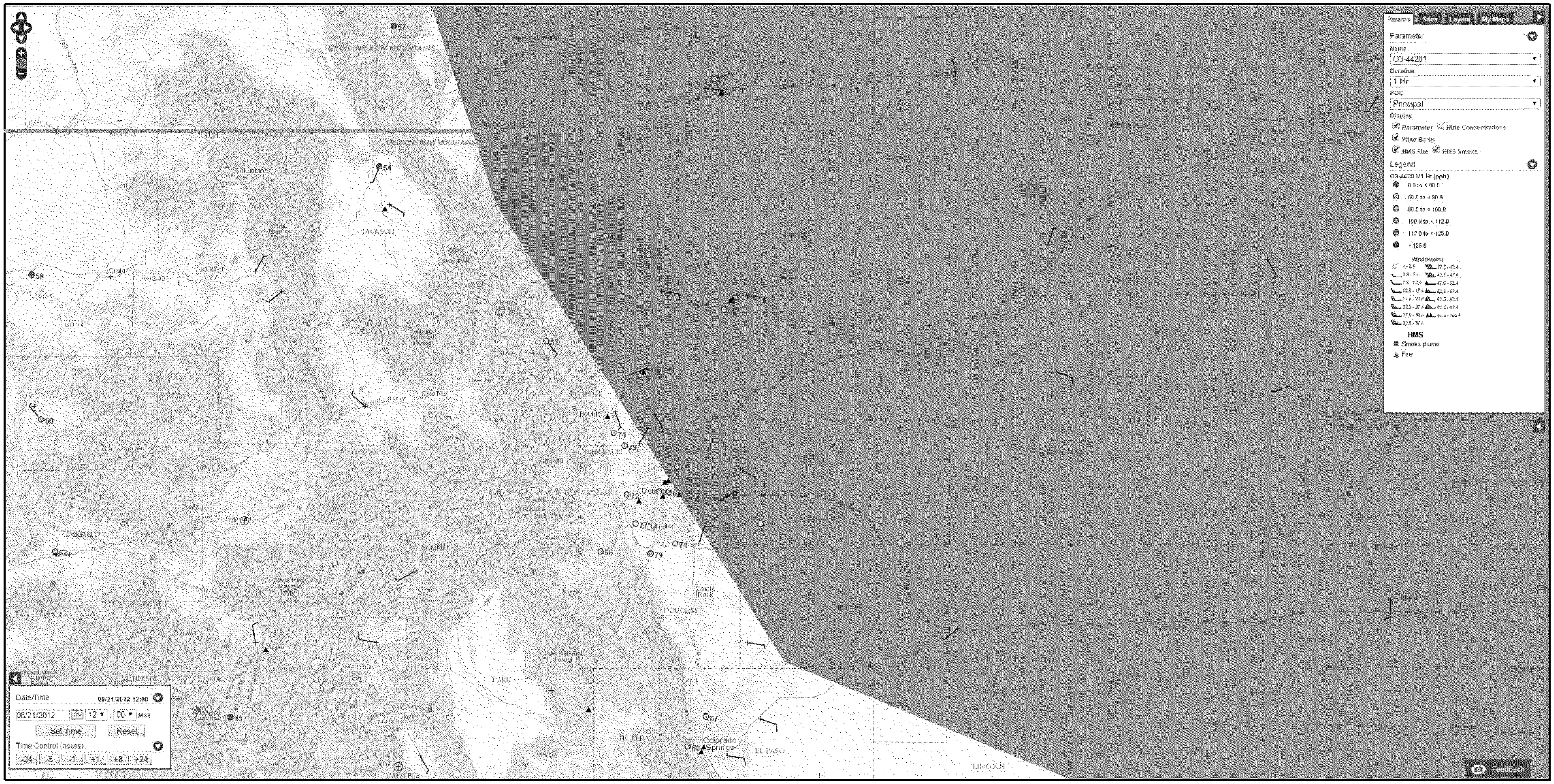

Figure 27. AirNow-Tech one-hour ozone concentrations, surface wind barbs, and most recent HMS analyzed smoke in gray for 12 MST August 21, 2012. Zoom in for a more detailed look. Colorado borders in blue.

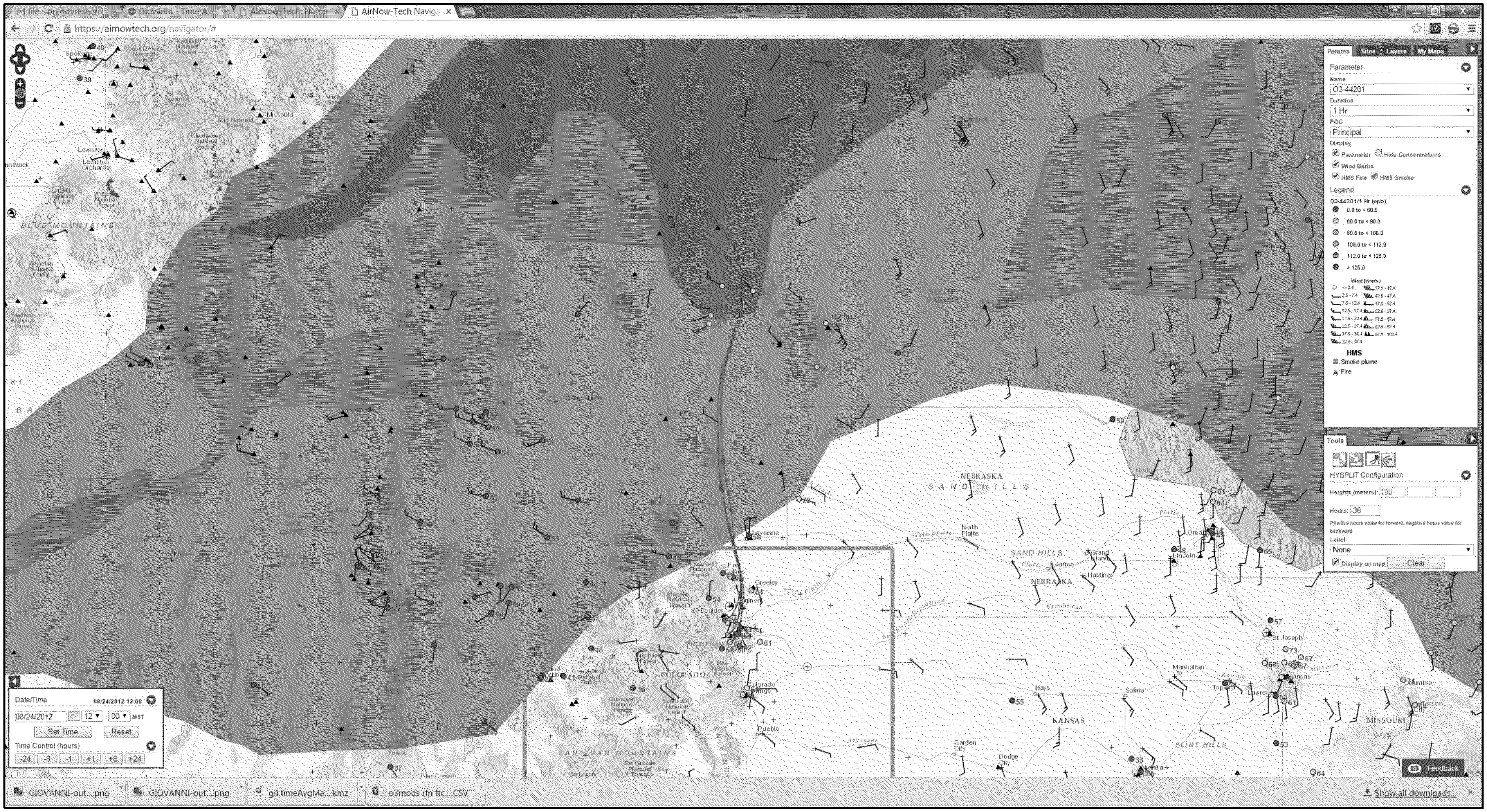

Figure 28. AirNow-Tech one-hour ozone concentrations, surface wind barbs, fires in red, and most recent HMS analyzed smoke in gray for 12 MST August 24, 2012. The NOAA HYSPLIT 36-hour back trajectories (green lines) arriving at 100 meters above the ground were calculated for an end time of 12 MST August 25, 2012, and show that ozone or its precursors from dense smoke in Wyoming and Montana could have been transported into the Front Range. Zoom in for a more detailed look. Colorado borders in blue.

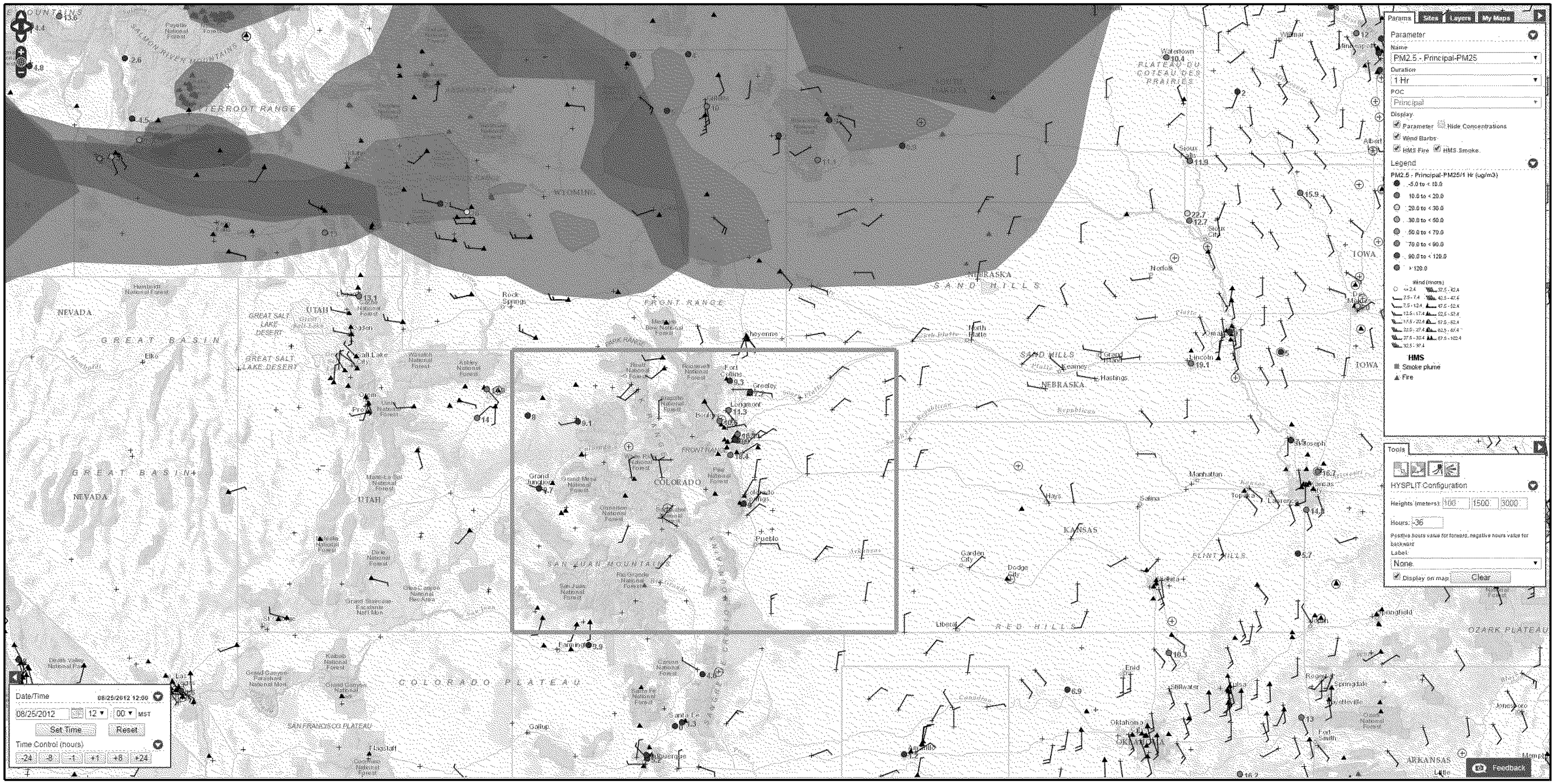

Figure 29. AirNow-Tech one-hour ozone concentrations, surface wind barbs, fires in red, and most recent HMS analyzed smoke in gray for 12 MST August 25, 2012. Zoom in for a more detailed look. Colorado borders in blues.

August 31, 2012

The AirNow-Tech composite products in Figure 30 show smoke in eastern Colorado that moved into the Platte Valley late on August 30 and was still concentrated in Weld and Larimer Counties during the morning hours of August 31. Figure 30 also shows anomalously high PM2.5 concentrations of 103.5 ug/m^3 and 136.1 ug/m^3 at Greeley and Longmont, respectively, with much lower concentrations in the Denver area. Although no analyzed smoke is apparent in Figure 31 for 12 MST on August 25, very high concentrations of smoke-related PM2.5 (31.8 ug/m3 and 97.4 ug/m3 at Fort Collins and Greeley, respectively) continued in the Platte Valley north of Denver with far lower concentrations in the Denver area. This smoke may have contributed to an exceedance at the Fort Collins West site. Ozone forecast regression models showed residuals of +3 ppb, +8 ppb, and +14 ppb at Rocky Flats North, Greeley, and Ft. Collins West, respectively. These data suggest that the 80 ppb daily max 8-hour ozone concentration at Fort Collins West (Table 1) was heavily influenced by smoke-related ozone.

August 17, 2013

While no smoke regression products were available for this day, The AirNow-Tech composite products for 12 MST on August 17 in Figures 32 and 33 show dense smoke in eastern Colorado from large fires in western states. Since regression results were not available, carbon monoxide plots from the Atmospheric Infrared Sounder (AIRS) have been added in Figures 34 and 35. Carbon monoxide is a relatively conservative tracer of combustion emissions, and it can be used to track the long-range influence of smoke from large-scale fire activity. The plots in these two figures were generated at the NASA Giovanni website and show the AIRS AIRX3STD level III version 6 daytime (ascending pass of the Aqua satellite that contains the AIRS instrument) time-average carbon monoxide in ppmv for August 17. Figure 34 shows the carbon monoxide in a layer centered on 650 mb which represents much of the boundary layer and the troposphere, and Figure 35 shows the carbon monoxide in a layer centered on 850 mb which is more representative of surface conditions. A description of the weighting of carbon monoxide at the levels included in each layer can be found in the documentation on the AIRS product at: http://disc.gsfc.nasa.gov/uui/datasets/AIRX3STD_006/summary#documentation. Both plots show anomalously high carbon monoxide concentrations of roughly 120 to 150 parts per billion over eastern Colorado and general patterns of high carbon monoxide that align with the smoke in Figures 32 and 33. Figure 35 certainly provides evidence that the smoke and any smoke-related ozone likely affected surface monitors. These data suggest that the 86 ppb, 84 ppb, and 87 ppb daily max 8-hour ozone concentrations at Rocky Flats, NREL, and Fort Collins West respectively, (Table 1) were heavily influenced by smoke-related ozone.

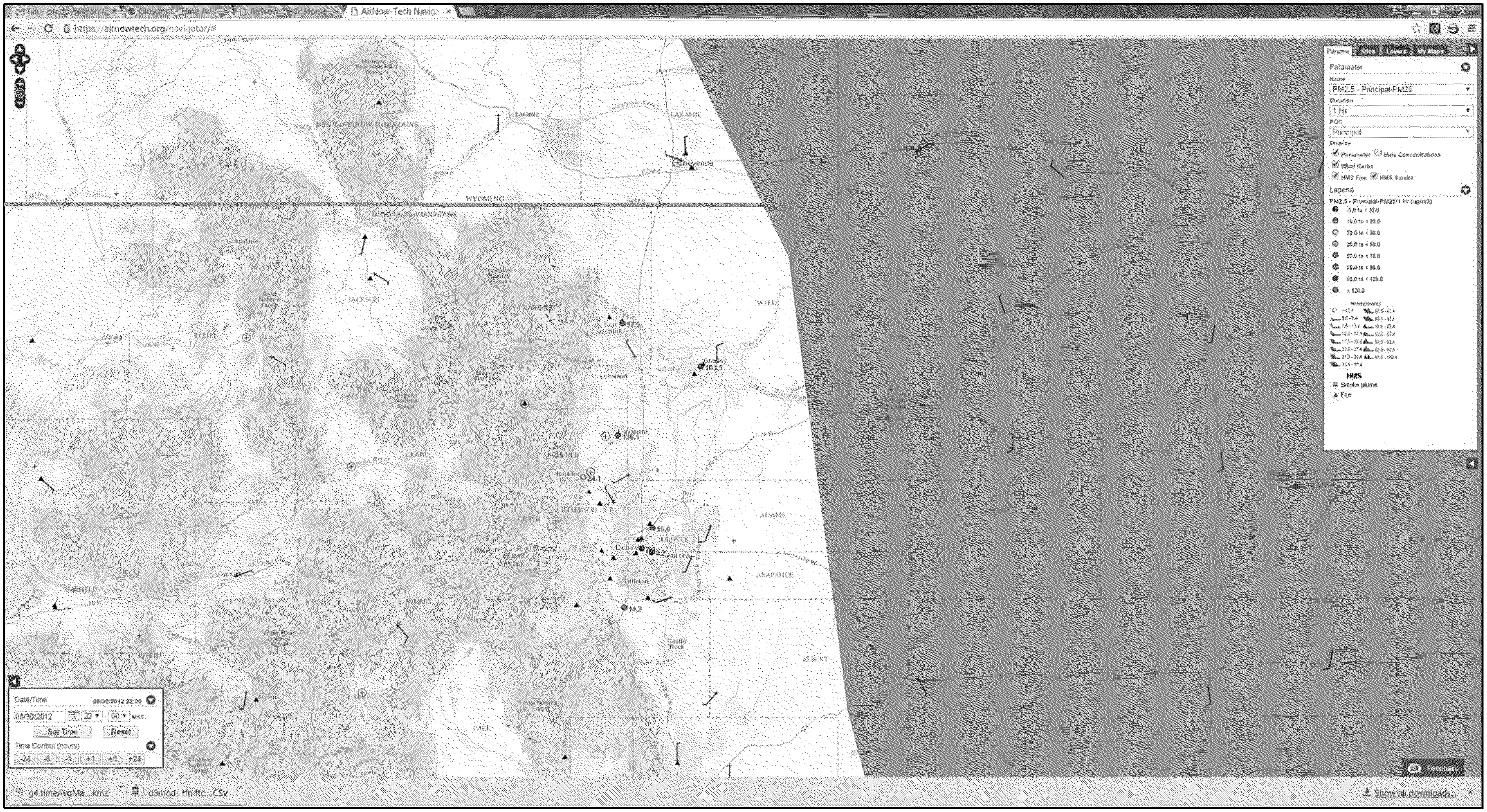

Figure 30. AirNow-Tech one-hour ozone concentrations, surface wind barbs, and most recent HMS analyzed smoke in gray for 12 MST August 30, 2012. Zoom in for a more detailed look. Colorado borders in blue.

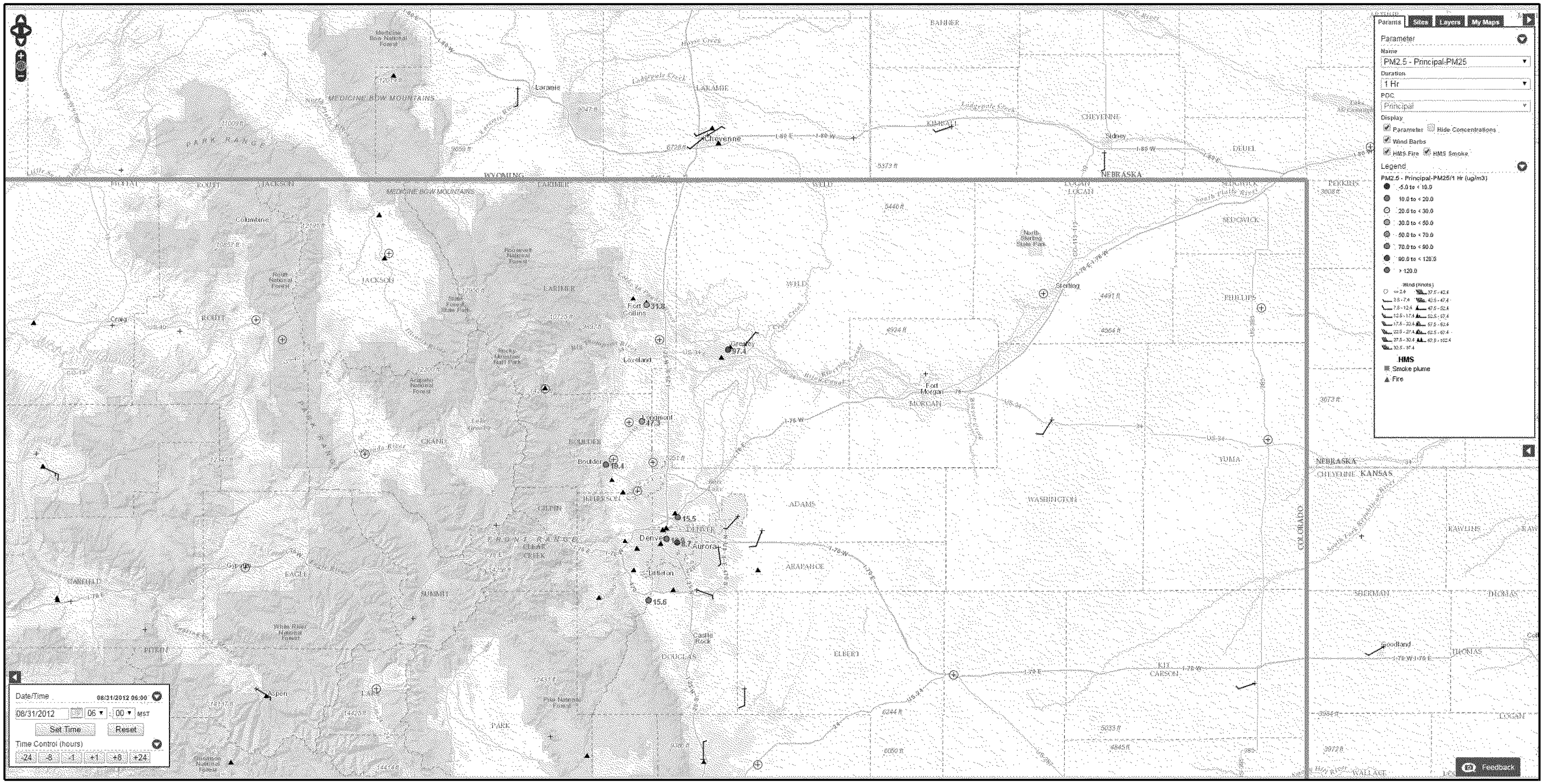

Figure 31. AirNow-Tech one-hour ozone concentrations and surface wind barbs for 12 MST August 31, 2012. Zoom in for a more detailed look. Colorado borders in blue.

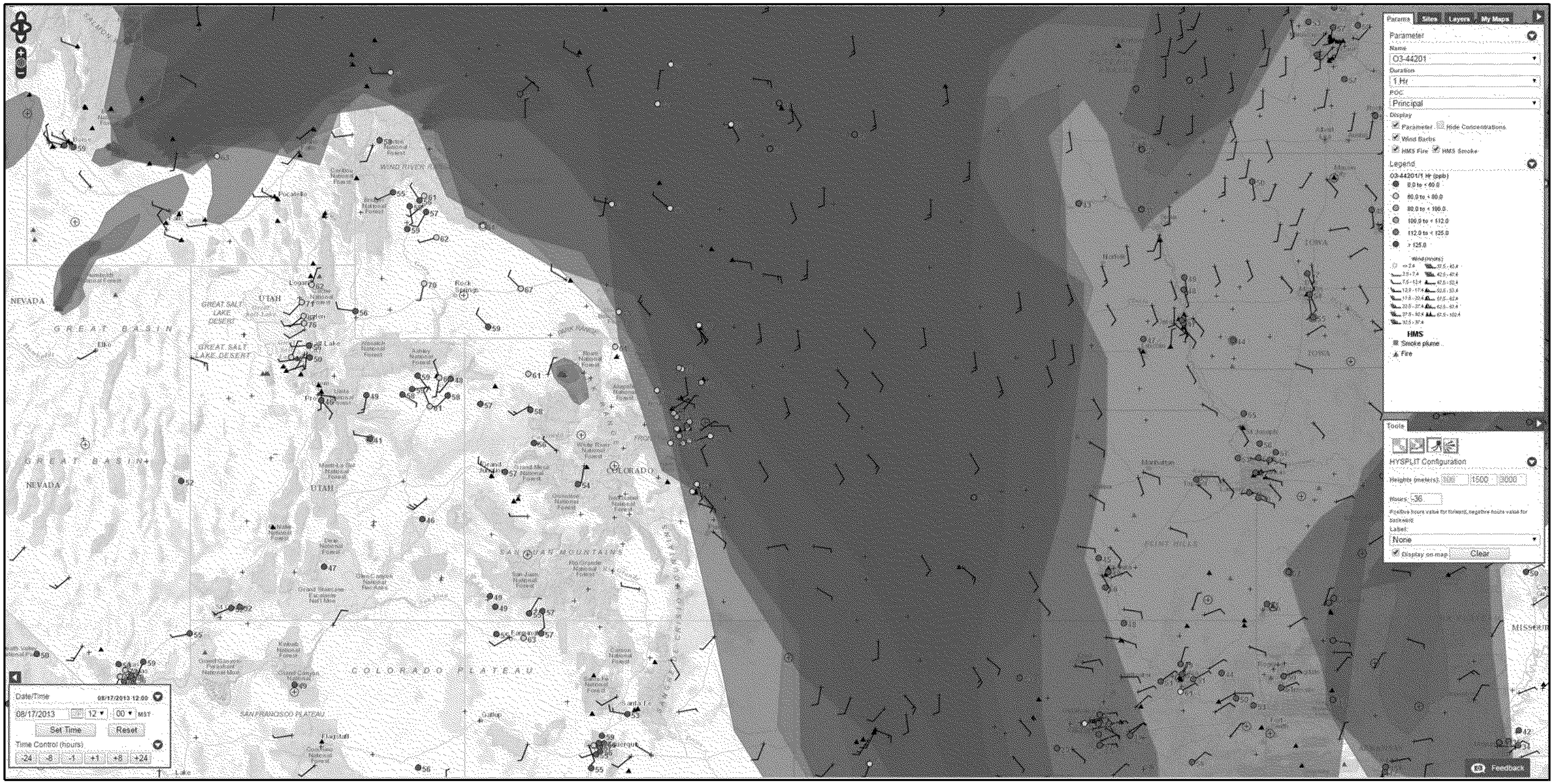

Figure 32. AirNow-Tech one-hour ozone concentrations, surface wind barbs, fires in red, and most recent HMS analyzed smoke in gray for 12 MST August 17, 2013. Zoom in for a more detailed look.

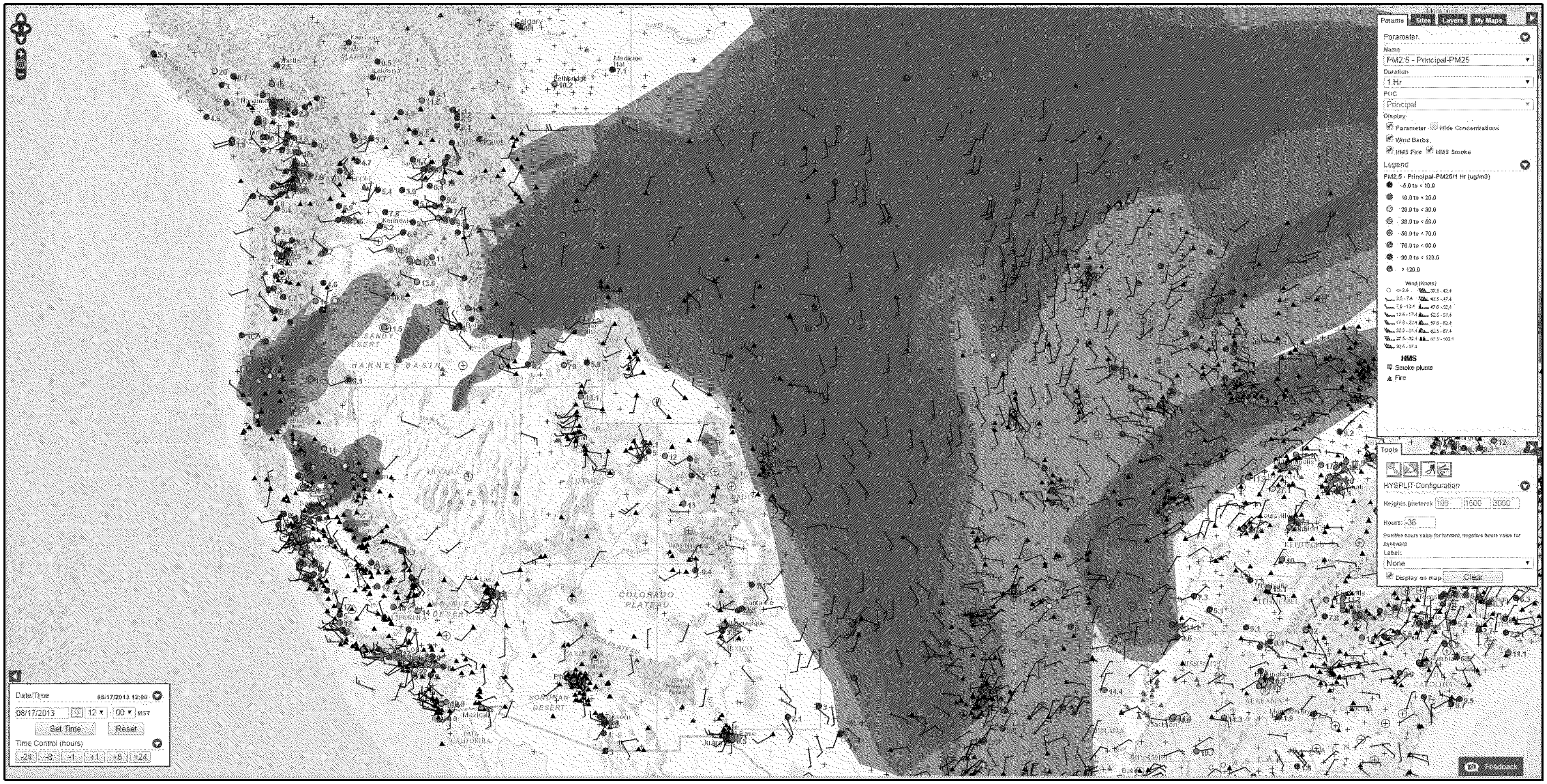

Figure 33. AirNow-Tech one-hour ozone concentrations, surface wind barbs, fires in red, and most recent HMS analyzed smoke in gray for 12 MST August 17, 2013. Zoom in for a more detailed look.

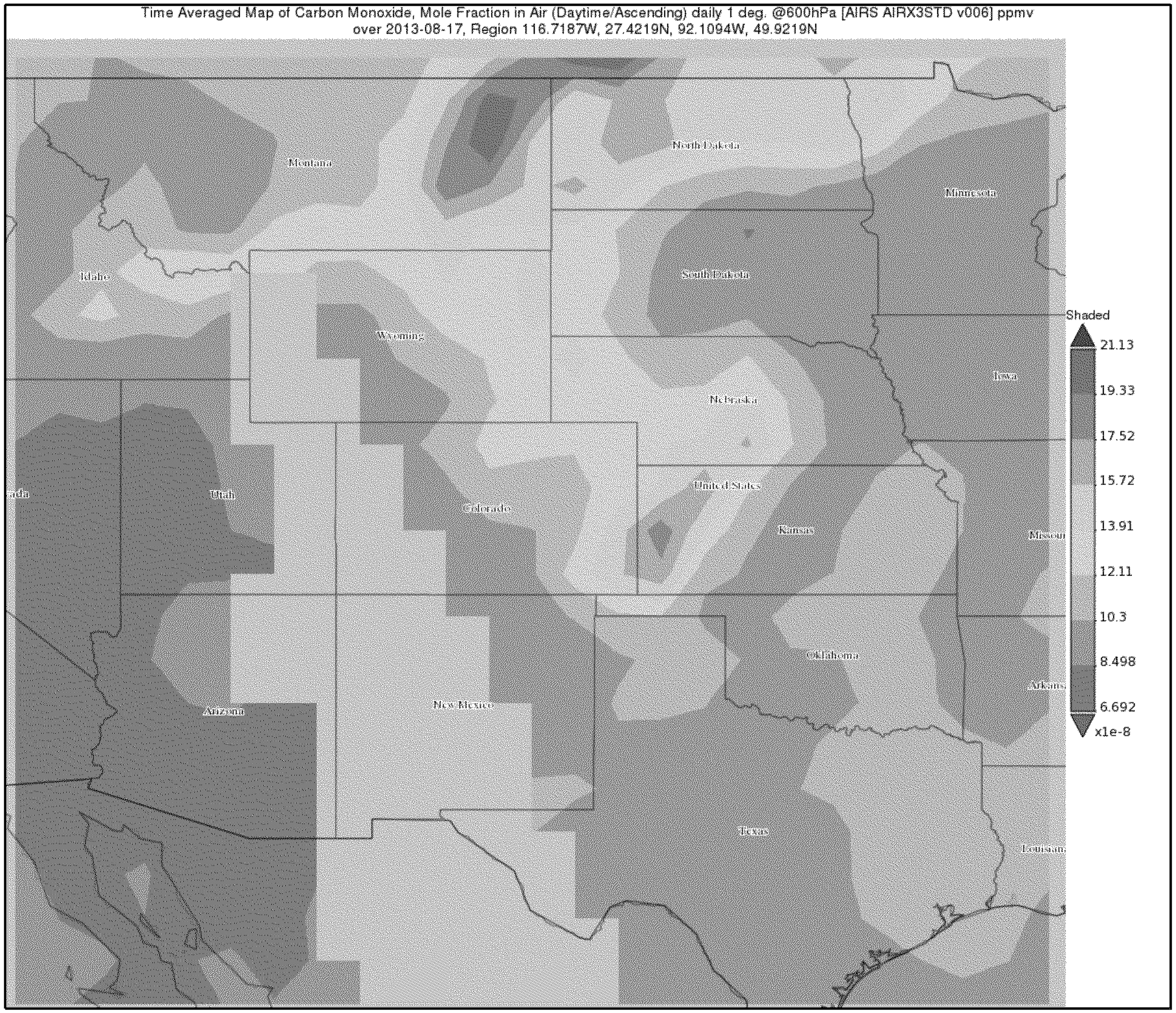

Figure 34. AIRS level 3 version 006 carbon monoxide concentrations in ppmv from the daytime ascending pass of the Aqua satellite for a layer centered on 600 mb on August 17, 2013. Zoom in for a more detailed look.

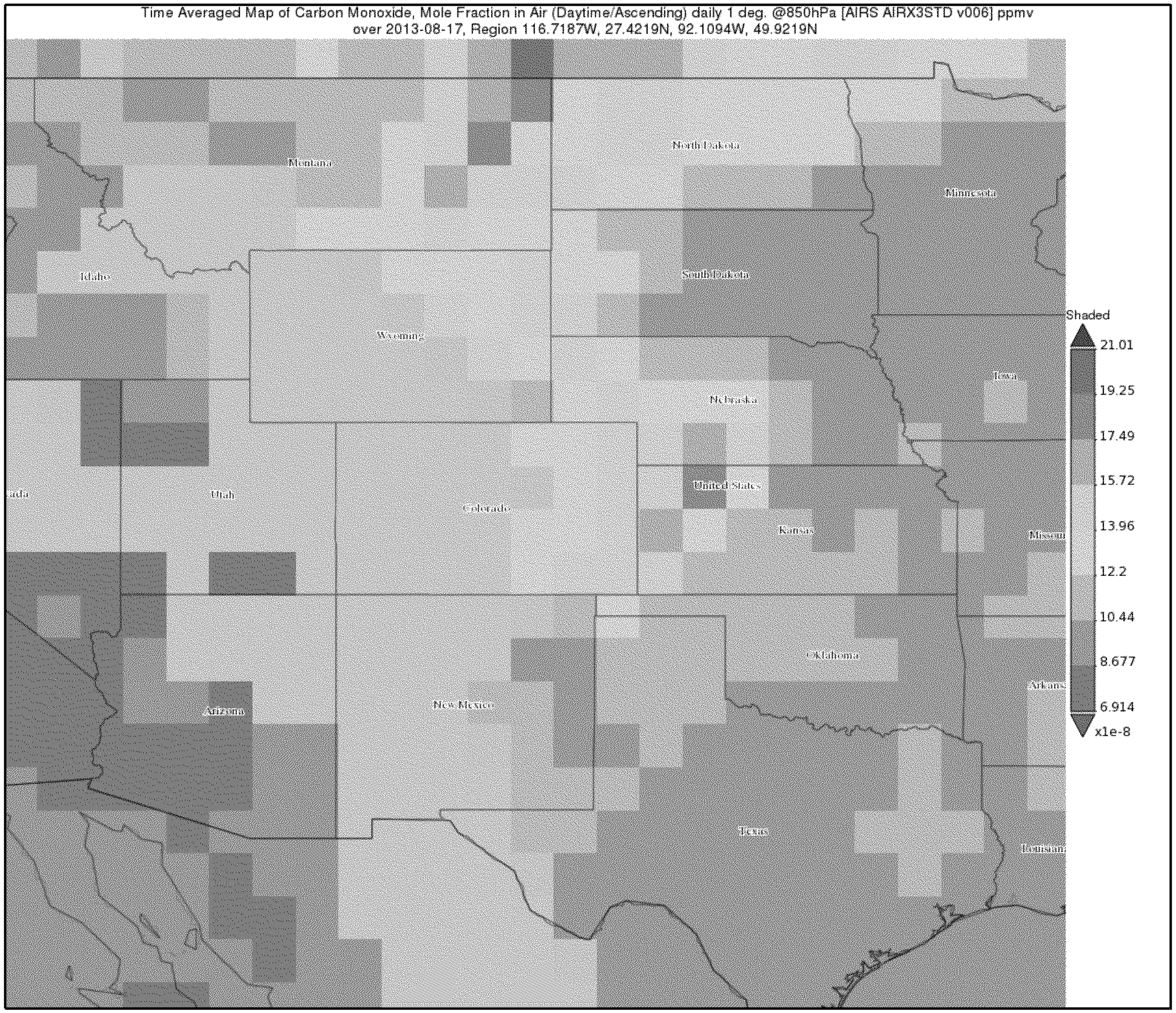

Figure 35. AIRS level 3 version 006 carbon monoxide concentrations in ppmv from the daytime ascending pass of the Aqua satellite for a layer centered on 850 mb on August 17, 2013. Zoom in for a more detailed look.

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